

BULLETIN
of the
American Association of
Petroleum Geologists

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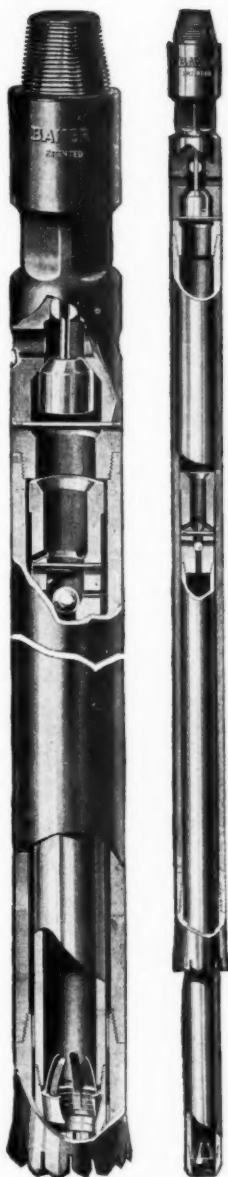
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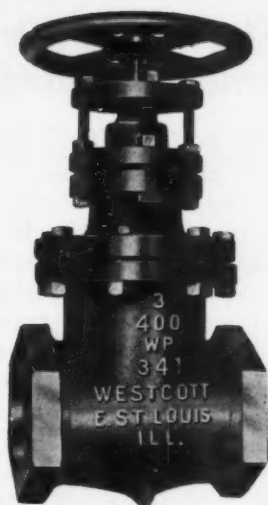
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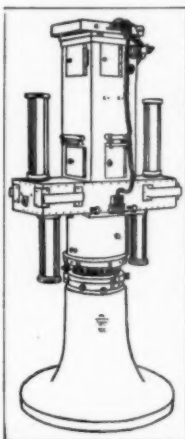
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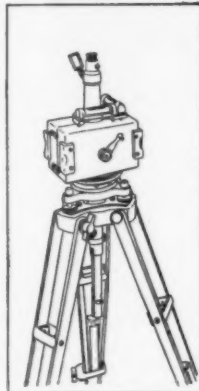


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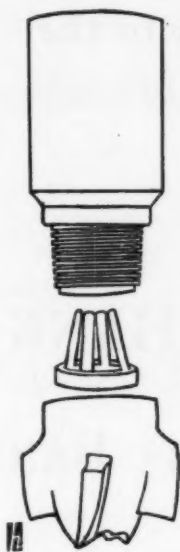
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AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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BULLETIN
of the
**AMERICAN ASSOCIATION OF
PETROLEUM GEOLOGISTS**

JANUARY 1929

STUDIES IN DIFFERENTIAL COMPACTION¹

C. M. NEVIN² and R. E. SHERRILL³
Ithaca, N. Y.

ABSTRACT

This series of laboratory experiments is intended to illustrate what may be expected in a region where differential compaction has occurred. The paper contains a discussion of the increase of dip with depth, the type of deformation that results, the relative importance of beds around and over the hill, the effect of two hills, and the effect of rejuvenation. Criteria are given by which a compaction fold may be recognized. A very important rôle of differential compaction is directive, and it is shown that this rôle may determine the subsurface attitude and the surface reflection of folds which owe a large part of their deformation to forces of a very different nature.

INTRODUCTION

Of all the areas in the Mid-Continent field, that of north-central Oklahoma is the most fascinating from a geological viewpoint, not only because of the structures with which the oil is associated, but also because of the manner in which they have been reflected at the surface. Undoubtedly differential compaction of sediments has occurred, but to what extent it has controlled or aided in the formation of the surface and subsurface structures is a moot question.

If it were possible to determine the influence of differential compaction in sediments under a variety of conditions, thus making it possible to evaluate its effects and to separate them from those of the complex forces which have stressed north-central Oklahoma, the problem

¹Manuscript received by the editor, October 22, 1928.

²Geology department, Cornell University.

³Eleanor Tatum Long graduate scholar in structural geology, Cornell University.

of the origin of the structures in that area would be greatly simplified. In attempting to do this, a laboratory study was made of differential compaction. This paper contains a discussion of the results.

The fact has long been recognized that most sediments suffer a loss in volume due to compaction under the influence of their own weight, and the probability that this compaction would result in deformation of the strata when deposited over a relatively incompressible body was pointed out by Blackwelder¹ as a possible explanation for the origin of certain of the Mid-Continent structures. Different phases of the application of this theory have been discussed by Powers,² Monnett,³ Hedberg,⁴ and others. That compaction is a factor in the structures of this area is admitted by most, if not all, geologists. Few, however, now believe that differential compaction alone is a complete explanation for the origin of all the folds known to exist here. What, then, is the rôle of compaction?

When an attempt is made to answer this question, the need of additional qualitative and quantitative data immediately becomes evident. In a shale section of uninterrupted deposition, where the amount of overburden can be determined, the work of Hedberg⁵ has made it possible to ascertain the approximate height of a hill that would be necessary to form, by differential compaction, a given structure at a known elevation above the hill. Thus we are able to determine whether or not the topographic relief that is known to exist under a structure is of a sufficient order of magnitude to have given the fold observed, and we can judge, in a general way, how much of the fold could have been formed by differential compaction.

Another very important part of the subject, and one which has received little consideration, has to do with the attitude of the fold above the hill; the shape of the fold as it would appear in vertical section; the thinning of sediments above the hill and thickening off structure; the type of folding, whether in relatively competent or incompetent beds;

¹Eliot Blackwelder, "The Origin of Central Kansas Oil Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), pp. 89-94.

²Sidney Powers, "Reflected Buried Hills and Their Importance in Petroleum Geology," *Econ. Geol.*, Vol. 17 (1922), pp. 233-59.

³V. E. Monnett, "Possible Origin of Some of the Structures of the Mid-Continent Oil Field," *Econ. Geol.*, Vol. 17 (1922), pp. 194-200.

⁴H. D. Hedberg, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1035-72.

⁵H. D. Hedberg, *op. cit.*

the probability or possibility of faulting; the area affected at the surface and at depth; the necessity of compactible sediments around the hill and the effect of beds over the hill; the inclination of the crest line and the axial line of the fold; the effect of more than one hill, their distance apart, and shape; and the effect of a rejuvenation of the hill.

Considering this phase of the subject, the following series of experiments were undertaken in the sedimentation laboratory at Cornell University.

Acknowledgments.—These studies in differential compaction were suggested by Sidney Powers and K. C. Heald, and during the experimental work their interest was very helpful to the authors. In addition, the manuscript was reviewed by Dr. Heald and greatly strengthened by constructive criticism. During the initial experiments D. W. Trainer, Jr., rendered valuable assistance.

EXPERIMENTS IN DIFFERENTIAL COMPACTION

The first experiments made use of a tank 1 foot high, 5 feet long and 6 inches wide, with plate glass sides and metal base and ends. In order that a greater overburden might be obtained, it was later found advisable to replace this with a similar tank 30 inches high and 4 feet long. Plaster of Paris hills, tightly cemented to the glass sides of the tank, formed the incompressible element. To simulate as wide a variety of conditions as possible, different shapes and sizes of hills were used throughout the course of the work.

A white clay from South Carolina formed the bulk of the clay beds, being interlayered with thin markers of a reddish-brown clay, and, in some of the experiments, with a layer of sand.

The clay was added as a very thin soup, each white layer being allowed to settle completely before adding the red marker or the sand, so that the contacts would be fairly sharp. Only clay was used until the hill was covered.

To simulate wave action that would ordinarily be found above a buried hill upon which shallow-water deposits were being formed, it was necessary now and then to agitate the water. This prevented the sediments from piling up over the hill-top; consequently, it was possible to lay down an almost level marker.

Above the hill the beds were deposited with a few markers until the water on the depositional surface became shallow. The sediments were then quickly covered with a 2- or 3-inch layer of sand, on top of which shot was added. The sand was used so as to distribute the weight of

the shot evenly and to prevent it from going down through the soft clay. This added load above the sediments was put on so quickly that differential compaction between the section directly above the hill and that on the sides of the hill was not immediately apparent. As a result, the top of the shot layer was deposited as a practically level marker.

RELATION TO NATURAL CONDITIONS

The procedure as outlined was intended to duplicate, as nearly as practicable, the actual field relations, and the extent to which this has been done requires some consideration.

Sediments as deposited in the laboratory were purer than commonly observed in the field—the clay had less sand in it and the sand less clay—resulting in some increase in potential compaction. Then, too, it is not practicable in the laboratory to deposit the clay in as finely divided a condition as is done in nature. This leads to the supposition that similar clays in the field had a higher initial porosity than in the experiments; but, on the other hand, wave and current action tend to shift the particles toward a denser arrangement. Taking these factors into consideration, it seems reasonable to suppose that the initial porosity of the Pennsylvanian shales of north-central Oklahoma was not greatly different from that of the clay as deposited in the experiments. In the case of carbonaceous shales, like the Cherokee, the initial porosity was, perhaps, considerably higher.

Since a plaster of Paris hill is formed of relatively incompressible material, it fulfills a necessary condition. The slopes of the sides of the hills used in the experiments ranged from 30° to 60° . Except in the case of fault scarps, few slopes of such steepness would be formed in a normal topographic cycle. However, steep slopes may have occurred on the pre-Pennsylvanian erosion surface, as may be inferred from the Thomas field.¹

The height of the hills used ranged from one-half to one-third the final thickness of the sedimentary section. This ratio here is considerably higher than in most of the buried hills of north-central Oklahoma. On the other hand, the shot may be considered as taking the place of a sedimentary column of greater thickness, and the actual exaggeration is thus reduced.

It is not possible in the laboratory to obtain overburdens comparable with those of nature; hence, the clay beds can not be reduced to as low a porosity as is characteristic of the shales of north-central Oklahoma.

¹Stuart K. Clark, "Thomas Oil Field, Kay County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 652.

Moreover, the friction on the sides and ends of the truck also tends to reduce the pressure on the lower beds. But, were it possible to use vertical pressures comparable with those in nature, it seems probable that the only noteworthy difference would be one of degree, and that the folds obtained in the experiments would merely be considerably accentuated.

As the sediments are compacted in the tank there is some drag on the glass plates, the effect of which may be noticed in some of the pictures where a thin film of the colored marker was left behind, tending to destroy the sharpness of the contacts. This was greater in the sands, but it could be almost eliminated by keeping the glass plates perfectly clean. The effect of drag was carefully observed to determine whether it vitiated the influence of the hill. It was found that the strata moved downward as a whole, were not bowed up on the sides, and the principal effect of friction was to prevent the weight of the shot from exerting as great a pressure on the lower beds as it otherwise would have done.

In gravitational compaction the time element is very important, but it can not be duplicated in the laboratory, nor can its effect be estimated. After sediments have become consolidated, the application of an ordinary stress is not very effective unless extended through a considerable period of time. Thus a thick and relatively competent limestone bed, in a sedimentary series above a buried hill, may yield by folding under the gravitational weight of overlying material, but only when the stress is long continued. With recently deposited sediments, such as the incompetent material used in the experiments, time as an effective agent is not so important. For example, after the addition of the shot, slight compaction of the sediments and consequent increase in the degree of folding could be noticed for a few days, after which no appreciable change could be detected during a period of several weeks.

In general, then, though the laboratory conditions differ in several particulars from those of nature, the principles involved are the same, and the field conditions are fulfilled to such an extent that the results obtained are of value in interpreting natural structures of similar origin, and enable us to understand some of the peculiar features noticed in the folds of north-central Oklahoma, where differential compaction has had its influence.

GENERAL CONSIDERATIONS

Water-deposited muds and clays are consolidated chiefly by compaction, since the pore spaces between the grains are so minute that there is little free circulation of water and thus very little opportunity

for cementation by infiltration. Compression, therefore, is the active factor in reducing the porosity of such sediments, and its efficacy depends largely on the ease with which the connate pore water may escape. When a clay is freshly deposited, the pore spaces are all interconnected and the deposition of even a small amount of additional sediment will upset the equilibrium of the contained pore water, some of which will move toward the point of easiest relief, and the clay will decrease in volume. Hence the greatest compaction of muds always occurs during the early stages. Later, when an initial porosity ranging from 60 to 80 per cent has been reduced by compaction to about 20 per cent, and the original clay has become a shale, the pore spaces are no longer perfectly connected, and the pore water is thereafter displaced only with difficulty. In fact, recrystallization, which has been going on to a greater or less degree throughout the entire process, is perhaps a dominant factor in the final stages of compaction. This, briefly, is the history of the ordinary shale, and in areas of little or no deformation such a decrease in porosity has been attributed to gravitational compaction, in which the weight of the overlying sediments has furnished the stress, and the resulting shrinkage in volume has been assumed to be entirely vertical.

It is admitted that vertical shrinkage is the dominant change. However, it would seem reasonable to suggest that, at least during the early stages, there would be a considerable transmission of stress laterally, with a reduction of porosity in a horizontal direction. If this is true, there would be a tendency for the clay to compact laterally, especially if deposited upon an uneven surface, such as a buried hill, with a consequent thinning of its section above the crest of the hill and a thickening off structure.

A muddy water just above the zone of settling acts as a true fluid, exerting a stress in all directions, and it would be strange indeed if the watery mud as it settles out should immediately act as a solid body, especially since its particles are in a state of "open packing." Would it not seem more logical to imagine a progressive change from a true liquid condition, in which the horizontal stress is equal to the vertical, through a stage in which the horizontal stress may be half the vertical stress, to a solid condition in which the horizontal transmission of the weight of overlying sediment is negligible?

To test this idea, two circular pieces of steel $2\frac{1}{4}$ inches in diameter and $1\frac{1}{4}$ inches thick were machined so as to give a perfect hemispherical cavity with a 1-inch radius. A $\frac{1}{8}$ -inch copper tube was placed in a drilled hole near the top of each cavity and soldered so as to be flush on

the inside. A piece of thin dental rubber was cemented across the 2-inch front of each cavity, care being taken to stretch it lightly and evenly. The copper tubing was bent so that one of these diaphragms could be laid flat and the other held vertically. Sufficient glass tubing was then attached so that, when the diaphragms were in position in the sedimentation tank, the tubing would project above the highest water level, and a stop-cock, which was part of the tubing, would remain immersed.

The diaphragms were then filled with water, care being taken to expel all of the air, and one placed near each end of the tank. Additional water was added to the tubes until the water level in them exactly corresponded to that in the tank, and with such an adjustment the diaphragms were perfectly flat and under no stress. Addition of any sediment would immediately exert an unbalanced stress on the diaphragm and move it inward, the least movement being reflected by raising the water level in the tube. Because of the very thin rubber used and the relative areas of the face of the diaphragm and the cross section of the tube, this apparatus proved to be quite sensitive.

While sediments were being deposited, the stop-cock in the line of tubing was closed, care being taken to see that the water level in the tube and in the tank exactly corresponded, so that the diaphragm would remain flat and unstressed. Since water is practically incompressible, the addition of sediments did not affect the diaphragm as long as the stop-cock was closed. Whenever a stress measurement was desired, a compressed-air line was attached to the tubing, the stop-cock opened and the air pressure necessary to keep the water level in the tube at the same height as that in the tank read on a water manometer. With a little practice it was possible to confine the movement of the water level in the tube to $\frac{1}{2}$ inch or less, thus preventing distortion of the sediments about the face of the diaphragm.

Table I summarizes the results, and Plates 1 and 2 show the different stages of sedimentation during the measurements.

Although this method of measurement is not perfect, still it shows rather conclusively that, in the initial stages of consolidation, a mud is

TABLE I

Stages	Horizontal Stress*	Vertical Stress*	Ratio of Horizontal to Vertical
Plate 1, Fig. 1.....	1.50	1.75	.86
Plate 1, Fig. 2.....	2.00	2.50	.80
Plate 1, Fig. 3.....	4.15	5.25	.78
Plate 2, Fig. 4.....	5.75	7.50	.77

*Measured in inches of water.

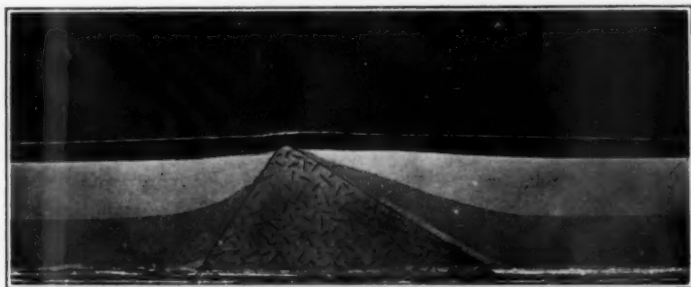


FIG. 1



FIG. 2

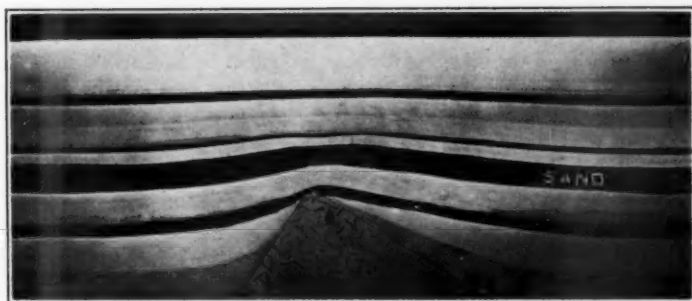


FIG. 3

Different stages in compaction over an asymmetrical hill. Reduction about 2/7.

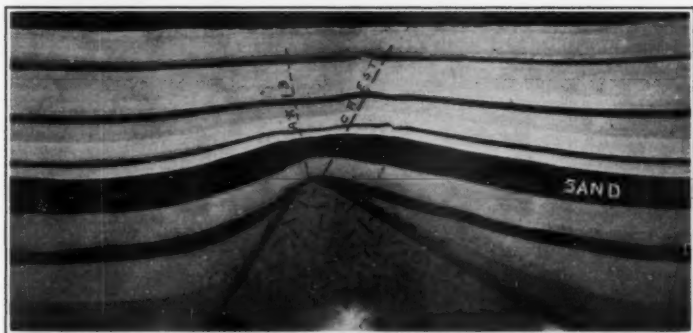


FIG. 4

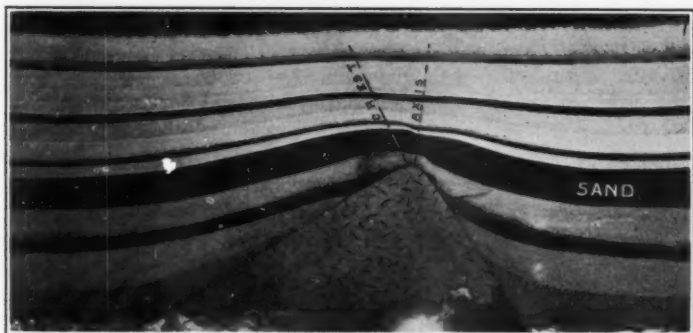


FIG. 5

A more advanced stage than Plate 1. Figures 4 and 5 represent the fold as seen on opposite sides of the deposition tank. Reduction about 2/5.

far removed from a solid condition, and that it transmits laterally a considerable part of the weight of overlying material. As the "open-packing" of the clay particles is broken down and a tighter, denser arrangement is assumed, less and less horizontal stress is transmitted, until finally the sediment acts like a true solid.

A further question of considerable interest is, what happens to the pore water that is squeezed out of the clay? In the early stages, especially if the mud is homogeneous, the displaced water will move upward toward the place of lower pressure. Or better still, since the pore spaces are all perfectly connected, the sediment will move down through the water, which may be considered as stationary. Later, when many of the pore spaces are disconnected, the easiest path for the water *may be* in a lateral or even downward direction to a coarser-grained bed. It was noticed during a trial run, when the hill was not completely cemented to the glass, that there was a concentrated circulation of water toward the sides of the hill. Undoubtedly this would have been magnified if there had been sand lenses interspersed in the clay and extending above the hill. Such a movement of pore water as a cause of migration and accumulation of oil and gas has been well summarized by Rich.¹

THINNING OF SEDIMENTS ABOVE THE HILL

One of the noticeable features of the experimental compaction structures is a thinning of the sediments over the hill. This is especially noteworthy since such a thinning in nature has ordinarily been attributed to uplift and erosion, or else to uplift during deposition, and in the experiments neither uplifts nor erosion were present. Doubtless the rate of compaction compared with that of deposition is one cause of such thinning. If compaction is relatively faster than deposition, then there will always be a tendency to deposit less material on the sides and the crest of the hill, especially during the early stages, before the hill has been deeply buried. For example, if in Plate 3, Figure 6, some additional shot were deposited, so as to form a level surface, the result would be a thickening of the shot off the fold and a relative thinning over the hill.

In addition, thinning of a bed may continue after deposition while the compaction folds are actively developing, and most of the final pictures in each series show such an effect. As a bed folds, it is elongated to cover a greater area, and, if it does not fault, it must become thinner through such stretching action. It might seem, then, that all the thinning is either a depositional feature or is due to stretching. That

¹J. L. Rich, "Moving Underground Water as a Primary Cause of the Migration and Accumulation of Oil and Gas," *Econ. Geol.*, Vol. 16 (1921), pp. 347-71.

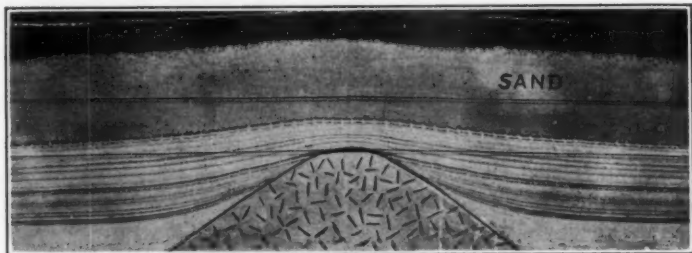


FIG. 6

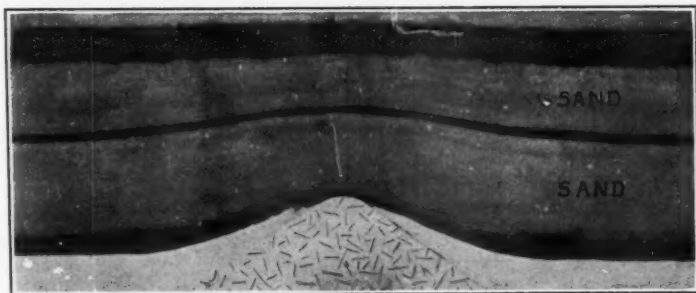


FIG. 7

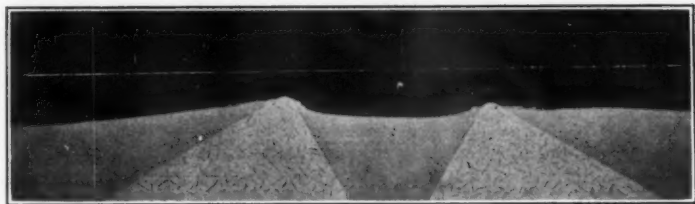


FIG. 8

Figures 6 and 7 show a similarity of folding which is independent of the type of material above the hill. Reduction about $2/5$.

Figure 8 represents an early stage in the deposition above two asymmetrical hills. Reduction about $2/7$.

this is not true was found by determining the volume of a section of normal off-structure thickness and comparing it with the volume of an equivalent section that had been folded. The folded section showed a loss of approximately 10 per cent of its original material, which would indicate an actual flow away from the stressed area. Thus, in soft sediments, where considerable gravitational flowage may occur, it is to be expected that the beds off structure will become thicker at the expense of those immediately over the hill.

The thinning is concentrated in a relatively small area, being especially marked near the crest, whereas the thickening is ordinarily spread throughout such a large area that it is hardly noticeable at any one place. Conversely, such a thickening is immediately evident if the off-structure area is limited, as is well illustrated in Plate 4, Figure 9, where the flow from two anticlines is concentrated in a narrow valley. A further proof of stretching and flow of sediments after deposition is given by the slump faults in Plate 2, Figure 4 and Figure 5, and the double crest in Plate 1, Figure 3.

INCREASE OF DIP WITH DEPTH

That folding due to differential compaction would increase in intensity with depth was recognized by Blackwelder¹ and has been accepted as a fact by later writers on the subject. The experimental verification of this feature is well shown in the illustrations and further demonstrated in Tables II, III, and IV.

In Table II are recorded the rates of dip away from the highest point of the fold in the final stage of the experiment over a symmetrical hill. Table IV is similar to Table II except that the hill is asymmetrical, and the dips away from the high point are recorded for the two limbs of the fold; and in Table III the same is shown for an earlier stage in the compaction of the sediments over the same hill. The letters representing the different horizons correspond with those in the figure indicated in the table.

Increase in the intensity of folding with depth is noticeable in all of these tables. Tables III and IV also indicate that, in the upward decrease in the intensity of folding over an asymmetrical hill, the ratio of the dips of the strata over the steep side of the hill to those over the side of gentler slope tends to remain about the same, and this ratio is determined by the form of the hill. The shape of the hill is, then, a most important factor in controlling the attitude of the fold, and its influence,

¹Eliot Blackwelder, *op. cit.*

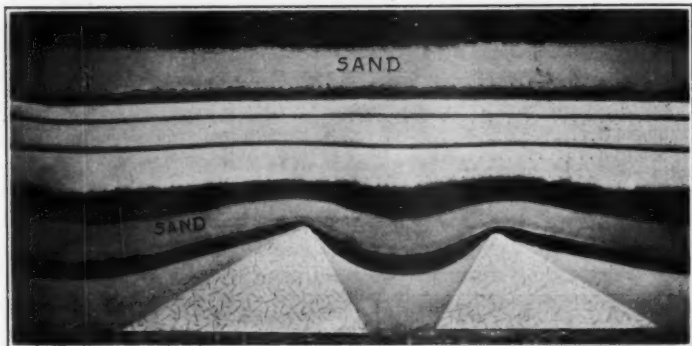


FIG. 9

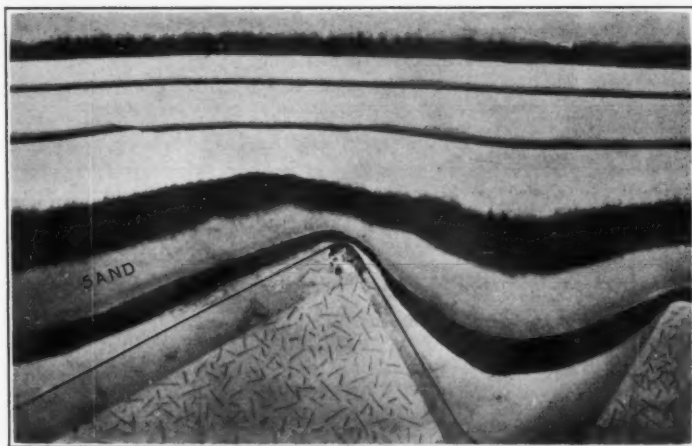


FIG. 10

Fig. 9. Folding over two asymmetrical hills, a later stage than that shown in Plate 3, Figure 8. Reduction about $1/3$.

Fig. 10. The left hill in Figure 9 has been uplifted an amount shown by its new position. Reduction about $1/2$.

TABLE II
SYMMETRICAL HILL
(Plate 3, Fig. 6)

Horizon	Degree of Dip
Bottom of C.....	2° 35'
Bottom of B.....	6° 15'
Bottom of A.....	10° 20'

TABLE III
ASYMMETRICAL HILL—EARLY STAGE
(Plate 1, Fig. 3)

Horizon	Degree of Dip Over 60° Side of Hill	Degree of Dip Over 30° Side of Hill
Bottom of E.....	0° 00'	0° 00'
Bottom of D.....	2° 10'	1° 30'
Bottom of C.....	4° 40'	3° 00'
Bottom of B.....	10° 00'	6° 20'
Bottom of A.....	22° 20'	10° 00'

TABLE IV
ASYMMETRICAL HILL—LATER STAGE
(Plate 2, Fig. 4)

Horizon	Degree of Dip Over 60° Side of Hill	Degree of Dip Over 30° Side of Hill
Bottom of E.....	2° 40'	1° 20'
Bottom of D.....	5° 50'	3° 10'
Bottom of C.....	10° 40'	7° 40'
Bottom of B.....	19° 30'	10° 45'
Bottom of A.....	31° 00'	15° 40'

in determining the *comparative rates* of dip in different directions on the fold, continues upward.

TYPE OF DEFORMATION

It has been assumed by many that folding in a region of simple structure and relatively competent beds is of the parallel or concentric type, and that the major movement has been between the bedding planes. The folding of incompetent material has usually been regarded as of the "similar" type, with a characteristic thickening of the sediments on the crests and in the troughs and a corresponding thinning on the flanks. The folds caused by differential compaction are in general open and simple, but conform neither to the parallel nor to the similar

type. The failure is truly incompetent, with a general absence of faulting and with the major adjustments in the beds themselves. These adjustments result in a thinning of the strata over the crests and on the flanks with a thickening off structure. For this type of failure the use of the term "compaction fold"—as distinct from either the parallel or the similar type—is suggested.

A further characteristic of compaction deformation seems to be that the area of a compaction anticline increases upward. This tendency may be seen in the folds obtained experimentally, and is particularly noticeable in Plate 3, Figure 6. Such spreading is surprising and the reasons for it are not readily to be found.

Where a symmetrical hill forms the incompressible element, as illustrated in Plate 3, Figure 6, the resulting compaction anticline is symmetrical. The line which bisects this fold—the "axial line"—also bisects the hill, is vertical, and coincides with a line connecting the highest points of the fold, here designated the crest line. But in folds developed over an asymmetrical hill, as illustrated in Plate 2, Figure 4 and Figure 5, the axial line and the crest line do not coincide. In this situation the axial line, as nearly as could be determined, lies intermediate in position between a vertical line passing through the top of the hill and a line bisecting the angle between the sides of the hill; the crest line passes through the top of the hill and is approximately parallel to its steep side. In an ideal asymmetrical anticline of the similar type, the crest line is parallel with the axial line, but it is displaced from this line toward the low-dipping limb; in the parallel type, the crest line is vertical down to the point where the curvature of the fold is acute, and there it becomes coincident with the axial line;¹ in the compaction type, the crest line and the axial line are both inclined, but in opposite directions.

The petroleum geologist is, as a rule, more interested in the highest point of a fold,—it is there that the dip reverses—and this is the point whose location is ordinarily determined. Any lack of superposition, at different horizons, of the highest points of a fold, is commonly referred to as a "migration of the axis." In an asymmetrical anticline, however, this is really due to the inclination of the crest line, which, except in perfect parallel folding, would always be inclined; and the location of the geometric axial plane is seldom determined. Since the location and inclination of the crest line are of great importance in the search for oil, it is significant that in an ideal asymmetrical compaction anticline the

¹Frederic H. Lahee, Discussion on "Graphic Method of Determining Location of Axis of Asymmetrical Folds at Various Depths," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5 (1921), p. 329.

crest line of the fold is inclined toward its steep side. This is directly opposite to the direction of inclination of the crest line in an ideal anticline of the similar type, while this line in a fold of the parallel type is vertical down to where the folding is acute.

There can be little doubt that the character of the beds above the hill has a marked effect on the inclination of the crest line. As these beds become more competent during differential compaction, it would be expected that the crest line would move toward the vertical, but it seems improbable that the influence of compaction, in its tendency to incline this line, would be entirely overcome. The net result should give a curved crest line that would be concave toward the steep side of the hill.

RELATIVE IMPORTANCE OF THE BEDS AROUND AND OVER THE HILL

In the consideration of differential compaction structures, it should be emphasized that the reduction in porosity of the sediments surrounding the incompressible element is the controlling factor in forming the structure, and the compactibility of the sediments above the hill is of minor importance. If the sediments surrounding the hill are composed entirely of sand, differential compaction is reduced to a minimum, and little deformation will result, even if all the section above the hill is a compressible clay. On the other hand, if a clay of high initial porosity surrounds the hill, a differential compaction structure will be formed even if the sediments above the incompressible element are composed entirely of sand.

To demonstrate this fact, an experiment was tried in which clay was deposited around the hill, and the entire sedimentary section above the hill was composed of sand. The result of this experiment is illustrated in Plate 3, Figure 7. A comparison of this fold with that in Plate 3, Figure 6, where clay comprised a considerable part of the section above the hill, indicates that the only significant difference is one of size—not of intensity.

It has been pointed out by Blackwelder,¹ Hedberg,² and others that the differential compaction which accompanies deposition results in an increase in the amount of material deposited off the structure, and the compaction of this material affects the folding of higher beds. However, it is the porosity reduction of the material surrounding the hill that makes possible this excess of material, and we come back to the original state-

¹Eliot Blackwelder, *op. cit.*

²H. D. Hedberg, *op. cit.*

ment that the factors of prime importance are the initial and final porosity of the sediments surrounding the incompressible element.

The initial porosity of the clay as deposited around the hills in the experiments was determined, and found to be about 70 per cent, and the approximate porosity and volume reduction of this clay at different stages is shown in Table V.

TABLE V

SYMMETRICAL HILL AT STAGE SHOWN IN PLATE 3, FIGURE 6		Per Cent
1.	Porosity of clay below horizon marked A	48
2.	Volume reduction of this clay	43
ASYMMETRICAL HILL AT STAGE SHOWN IN PLATE 1, FIGURE 3		
1.	Porosity of clay below horizon marked A	48
2.	Volume reduction of this clay	43
ASYMMETRICAL HILL AT STAGE SHOWN IN PLATE 2, FIGURE 4		
1.	Porosity of clay below horizon marked A	37
2.	Volume reduction of this clay	52

Note: The dip of the beds at various horizons for the above stages is shown in Tables II, III, and IV.

THE EFFECT OF TWO HILLS

In Plate 4, Figure 9, is shown the compaction structure that was formed over two asymmetrical hills with the steep slopes facing each other and so spaced that the horizontal distance between the tops of the hills is equal to about twice their height. Above each hill the strata arch into a compaction anticline, and over the valley a syncline is formed. When we examine the upward reflection of the syncline a significant feature is observed. Instead of appearing as a downfold throughout the entire section, as might be expected, it has entirely disappeared in the strata above the horizon marked C, and these upper beds show a distinct anticlinal tendency directly over the syncline.

If the area of a compaction anticline increases upward, it follows that two such anticlines might be spaced nearly enough together so that in their upward spreading they would merge and appear as one fold. This is what seems to have happened in Figure 9, and the final effect in the upper horizons, D and E, is a broad arch extending over both hills and the valley between.

It is natural to ask what would happen if the orientation of the hills was reversed so that the gentler slopes faced each other. If their distance apart was not changed, the only effect would probably be a more distinct upfolding of the composite arch, because the crest lines of the individual folds would be inclined toward each other, tending to unite the separate crests.

The ratio between the width of the valley and the height of the hills is of prime importance. Unfortunately, the length of the tank necessitated such a spacing that this ratio was smaller than would ordinarily occur in nature; hence, the merging of the anticlines was more marked than would commonly be observed. Most of the hills in a normal topographic relief are probably far enough apart so that compaction folds do not join.

THE EFFECT OF REJUVENATION

To illustrate the effect of a rejuvenation, wires were attached to the left hill in Plate 4, Figure 9, so that it might be gently raised after seeming compaction had ceased. A sheet of rubber was attached to the base of the hill in such a manner that it prevented flowage of the clay under the hill during and after uplifting. Plate 4, Figure 10, illustrates the attitude and character of the fold at the stage when the hill had been raised about one-fourth of its original height.

There is no noticeable change in the position of the crest of the fold, but there is a marked increase in the thinning of the strata near it. A part of this increased thinning is due to flow of the incompetent material away from the disturbed area, as indicated by a slight increase in the thickness of the strata off the fold. Also some of the thinning is a result of the stretching of the beds as they adjust themselves to cover a greater area, and doubtless additional compaction plays its part.

An increase in the degree of dip is apparent throughout the entire fold. This is greatest in the beds near the hill, and higher in the section it becomes progressively less. The fact that the uplift is reflected with such marked upward diminution of intensity is a natural result of the continued thinning of the incompetent strata over the disturbed area.

At the crest of the fold, in horizon C, there is a downfaulted block with the strata above and below upfolded. This peculiar association of down-faulting and up-folding is probably a result of the thinning of the underlying beds. Very likely if the rejuvenating stress had been applied more slowly this fractured area would have been able to adjust itself by stretching and flowing so that no visible faulting would have resulted.

It might seem, at first thought, that in the rejuvenation of a hill overlain by consolidated sediments the failure would be very different, but an analysis of the factors involved leads to the conclusion that the final results may be quite similar. If the uplift is so slow that it does not induce faulting, the actively developing fold would tend to stretch

and thin the beds. This thinning, with its attendant upward diminution of folding, would be less than it is in the rejuvenation experiments, since consolidated material would not flow from a disturbed area. During the rejuvenation of a buried hill, overlain by either consolidated or plastic sediments, the greatest amount of stretching is where the strata are already thinnest and hence weak. The position of this line of weakness was predetermined by the original compaction structure. In a symmetrical fold it is vertical and coincides with the crest line; in an asymmetrical fold it is inclined with the crest line and lies near by.

Thus we come to the important conclusion that the upward line of weakness established by differential compaction of unconsolidated material should exert a directive influence which, *in the absence of other factors*, would determine the attitude of any later folding due to a rejuvenation of the hill below.

It might be well to point out that when rejuvenation occurs after the lower beds have become consolidated and the upper horizons are still in a more or less plastic condition, we should expect a thinning throughout the section. This thinning would not decrease regularly upward from the hill, but in a zone where the sediments are unconsolidated it would increase and would seem to be abnormal.

In general, it would seem that differential compaction and periodic uplift would give a progressive thinning throughout the section, which would be similar in effect to a continuous uplift contemporaneous with sedimentation.

THE RÔLE OF DIFFERENTIAL COMPACTION

Occasionally it can be demonstrated that the topographic relief underlying a surface structure is of a sufficient order of magnitude to have formed it by differential compaction alone. Additional

proof that condensation forms anticlines is the fact that anticlines in Pennsylvanian strata overlie hills of 'Mississippi' lime where there is no folding in the base of the lime—several such hills have been found by drilling near Tulsa, Oklahoma.¹

As shown by the laboratory experiments, the presence of such structures necessarily implies that the buried hill is surrounded by compactible material, but it does not require any particular type of sediments for the overlying beds, since their principal rôle is merely one of weight. In all structures, where no factors other than differential compaction

¹Sidney Powers, "Reflected Buried Hills," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 428.

have had an influence, we should expect a thinning of the beds on the structure and a thickening off structure, an increase in the intensity of folding with depth, and a general absence of faulting.

Of the preceding criteria, thickening and thinning off and on structure are doubtless of the greatest value, especially while drilling an initial well. Thus a local excessive subnormal or supernormal thickness of formations in a stratigraphic section should make one suspicious of the near-by presence of a buried hill. On the other hand, absence of excessive thickening would not necessarily mean that there was no buried hill, since the flow of material from the thinned area may be spread throughout a considerable distance. Moreover, where the local normal sedimentary section is known, this criterion of excessive thickening or thinning may be used to check favorable data secured by other means, such as geophysical methods.

Another interesting possibility is the use of thickening where associated with a surface fold that changes to a syncline with depth. Experimentally such a fold was formed as the result of spreading and crowding between and over two hills. That such a relation occurs in nature is not certain, but it would seem that at least some surficial folds are of this type.¹ The log of a single test well on one of these folds would doubtless not show the change to a syncline as the fold died out with depth, but according to the experimental evidence it should show a thickening of the deeper formations.

Any specific structure, due entirely to compaction, should reflect in its outline the shape, size, and position of the underlying hill. For instance, a symmetrical fold at the surface should be almost directly superimposed over a symmetrical buried hill at depth and its closure would be a composite result of the height of the buried hill, the distance above the hill, and the amount of differential compaction in the underlying formations. An asymmetrical fold at the surface should indicate an asymmetrical buried hill at depth, because the inherent characteristics of a compaction fold and the fact that there is always more potential compaction off the steep side of the buried hill would tend to maintain the asymmetrical form of the fold throughout its entire vertical extent. Moreover, the high point of such an asymmetrical surface fold would not be directly above the buried hill, but would be displaced some distance toward the side of gentle slope, since with depth the crest line moves toward the steep side. The angle of inclination of this crest line seems to be largely controlled by the ratio of the slopes of the buried

¹Sidney Powers, personal communication.

hill and, naturally, the amount of migration of the crest is a function of the distance away from the hill.

Thus it is evident that the correct location of an initial test well on a structure that has been caused entirely by compaction is a simple matter only where the fold is symmetrical. If the surface fold is asymmetrical, it would seem that an indication of the angle of the crest line might be given by the amount of departure from a symmetrical shape,—the more nearly the fold is symmetrical, the less the crest line would be inclined to the vertical. There are no accurate data available to prove whether or not the ratio of the dips of a surface structure would be exactly the same as that of the underlying hill; although the laboratory experiments seemed to show a rather close agreement between these surface and subsurface ratios, the vertical height of the tank was too small to warrant a dependable conclusion. In addition to estimating the angle of migration of the crest line, a proper well location would also involve the depth from which the buried hill is being reflected. As a consequence of the principles illustrated by the laboratory experiments, it naturally follows that the initial well on an asymmetrical compaction fold should be located some distance down the steep side from the high point, if it is desired to strike the apex of the buried asymmetrical hill.

The preceding discussion applies to folds which owe their origin to differential compaction alone. These are the exception rather than the rule, and ordinarily the attitude of the fold has been modified by other factors which may have dominated it to such an extent that they have effectively obscured the influence of compaction. There is a complete gradation from the type of fold in which compaction has played the leading rôle to those in which it has had no influence.

A buried anticlinal fold may or may not have been a point of topographic relief, and, conversely, a buried hill may be a buried structural "high." In all places, however, where a buried hill is surrounded by compressible material, a compaction structure will be formed, and this structure will have its influence in any later rejuvenation.

If the buried hill is neither a structural "high" nor located along a line of weakness, we should not expect its local rejuvenation; but over it there exists a line of weakness established by compaction, and a regional uplift or warping might accentuate this weakness. This, however, is problematical and of minor importance in comparison with the commonly observed situation where the buried hill is also a structural "high" and hence a point of weakness.

Rejuvenation of a buried structural hill is not only possible, but it is the normal condition to expect if the region has undergone subsequent

stresses. The uplift of the hill itself would be controlled by a re-folding of the underlying structure, but, when the hill is surrounded by compactible sediments, the fold above it would necessarily be subject to the influence of compaction, and, as seen at the surface, it would be the composite result of differential compaction and of dynamic movements. These later developments would tend to follow the line of weakness established during differential compaction. The position of this line of weakness has already been pointed out. In general, it may be said that, with the possible exception of the ordinary absence of faulting, rejuvenated compaction folds should show the characteristics of a structure which owes its origin to compaction alone, but they would not necessarily be developed to an equal degree. The folding would increase in intensity with depth and would overlie a hill which would not have sufficient relief to have formed the structure by differential compaction alone. The thinning of the beds over the structure should be more marked and should be present throughout all of the section deposited prior to the rejuvenation, regardless of whether this uplift was periodic or continuous.

CONCLUSION

At several places in this paper, the writers are tempted to make a specific application to structures in north-central Oklahoma, but in that area so many other factors of equal or greater importance are involved that it seems best to reserve this for a later paper. However, the following conclusions are of general application.

1. Certain essential conditions must be fulfilled before differential compaction becomes effective. When these conditions are met, a compaction fold must result.
2. A compaction fold has in it certain inherent characteristics which are sufficiently different from those of any other type of folding to make it recognizable, and these same characteristics make it possible to detect the influence of compaction in many folds which owe a considerable part of their deformation to other factors.
3. Although differential compaction, unaided by other forces, may result in the formation of a fold of major significance, its rôle of greatest importance is directive, and in this rôle it may determine the subsurface attitude and the surface reflection of folds which owe a large part of their deformation to forces of a very different nature.

THE NATURE OF UPLIFTS IN NORTH-CENTRAL OKLAHOMA AND THEIR LOCAL EXPRESSION¹

C. M. NEVIN² and R. E. SHERRILL³
Ithaca, N. Y.

ABSTRACT

The relative importance of the forces which have stressed north-central Oklahoma, and the regional nature of the vertical stresses, are pointed out. There follows a discussion of vertical stresses and their local effect as determined by the pre-existing character of the pre-Cambrian complex. The theory is advanced for the origin of many of the structures by local differential movements in a mass of rock which is being regionally tilted by vertical stresses.

INTRODUCTION³

From the fact that many theories already exist concerning the origin of the structural features in north-central Oklahoma, it is evident that the problem is far from simple. Some of these theories have been formulated to explain the observed relations in some local part of the region. To-day, however, this north-central Oklahoma area forms a structural unit, and throughout most of geologic history it has acted as such — a structural unit that has undergone a common topographic and sedimentation development, with differing local expression.

If it were possible to establish firmly the few outstanding forces which have been effective, and to show the general nature of their action, a step could be taken toward a final solution of the origin of these economically important structural features. With this idea in mind, one of the major types of forces is here considered, namely, vertical stresses and their local effect as determined by the pre-existing character of the pre-Cambrian complex.

HAVE VERTICAL OR LATERAL STRESSES BEEN THE EFFECTIVE FORCES IN THIS AREA?

An answer to this question should be based on a consideration of the regional effect of the forces which have periodically stressed the

¹Manuscript received by the editor, November 7, 1928.

²Department of geology, Cornell University.

³The writers wish to acknowledge gratefully the constructive criticism of John L. Rich. His geological suggestions greatly strengthened this paper.

area. Undoubtedly each period of major deformation has expressed itself as an uplift, and movements such as warpings and regional tilts are not the result of a dominant lateral stress, but are, in reality, a reflection of true vertical stresses. The presence of numerous unconformities in the section, the fluctuating boundaries of the depositional seas, and the regional tilts at the close of the Devonian and after the Permian, are all indicative of vertical movements.

Though stress be transmitted through the basement complex, it is hardly conceivable that a lateral thrust of sufficient magnitude to affect so large an area would not leave behind abundant evidence. The one clear-cut example of such a deformation is seen in the Ouachita Mountains, and the thrust from this area has been used repeatedly to explain the origin of many present surface structures, some of them far removed from this zone. That lateral stresses occurred in the region is clearly proved, and according to Dake¹ the Ouachita mountain mass was overthrust and travelled as a sheet "scores of miles." However, such types of failure in general affect only a relatively narrow area in front of the overriding mass, and this seems to have been true of the Ouachita Mountains, for, although locally intense, the effect died out within a short distance and had only a minor influence upon deposition and the distribution of the shallow seas in north-central Oklahoma.²

Additional evidence is seen in the fact that the last slight regional westward tilting was sufficient to give a north and south strike to some of the formations, even though only a few score miles away. In formations older than Wewoka, the recent Oklahoma areal map clearly demonstrates this rapid dying-out of the effect of the Ouachita thrust, even before the central part of Hughes County is reached. Naturally, if this outstanding lateral stress had seemingly so little effect in north-central Oklahoma, the potency of possible similar stresses at other periods should be regarded with considerable doubt.

If an area is uplifted without tilting, it is recognized that vertical stresses have acted throughout the region as a whole, and a center of uplift is not sought. On the other hand, an explanation given by many for regional tilts is that there exists a center of uplift which carries with it the formations on all sides, and that, from this center, the strata dip in all directions, the degree of dip being steeper near the center of uplift and slowly dying away from it. However, the last tilting, which gave

¹C. L. Dake, "The Problem of the St. Peter Sandstone," *Bull. Missouri School of Mines*, Vol. 6 (1921), No. 1, p. 55.

²R. H. Dott, "Pennsylvanian Paleogeography," *Oklahoma Geol. Survey Bull.* 40-J (1927), p. 14.

the present westward dip to the formations in north-central Oklahoma, was not centered in the Ozarks, but affected a broad belt extending south into Texas. As suggested by Levorsen,¹ it seems probable that the Bend arch of Texas, the Ozark uplift, and the intervening area, are essentially a part of the same structural feature. It is important, therefore, that these vertical stresses should not be thought of as having radiated from the Ozarks as a center, since, in reality, they were truly regional in character.

The Ozarks may have been uplifted more than the surrounding area, for they were an old positive mass, seemingly a point of weakness in resistance to vertical stresses. In the same way, a point of weakness anywhere in the north-central Oklahoma area would show a relative uplift. From this it should not be inferred that vertical stresses were of uniform magnitude in the entire region at any one time, as they very probably showed local differences.

Vertical stresses which left the formations with their present west dip occurred after the deposition of the Permian beds, but evidence is plentiful that similar stresses, although not always of the same magnitude or extent, acted recurrently throughout the Paleozoic. They were extensive near the close of the Devonian and again near the end of the Mississippian, and the presence of many uplifts of smaller magnitude and areal extent is evidenced by the shiftings of the seas.

Thus, a consideration of the relative dominance of lateral or vertical stresses in this area seems decidedly to favor vertical forces, and it should again be emphasized that these vertical forces were regional in extent.

WHAT IS THE NATURE OF THE PRE-CAMBRIAN COMPLEX?

Any consideration of the failures in the Paleozoic sediments must take into account the structural, lithologic, and topographic character of the underlying pre-Cambrian complex.

Fath² advances reasons for supposing that in the basement rocks there exists a series of lines of weakness trending slightly east of north. Van der Gracht³ supports this idea, and says that the "original basal grain" in this part of the North American continent was seemingly north

¹A. I. Levorsen, "Convergence Studies in the Mid-Continent Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), p. 679.

²A. E. Fath, "Origin of the Faults, Anticlines and Buried Granite Ridges of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-C* (1920), pp. 75-80.

³W. A. J. M. van Waterschoot van der Gracht, "Discussion on the Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 302.

and south. Ruedemann,¹ in writing of this general area, says "the original strike of the pre-Cambrian rocks seems to have been in a north-south direction, with a tendency to turn northeast."

Judging from the pre-Cambrian areas now seen at the surface, there should be, in addition to these prominent zones of weakness, scattered patches of rather weak, cleavable material interspersed in massive resistant bodies.

Lithologically, pre-Cambrian rocks, because of original variations, exhibit marked differences in their resistance to stress. Pre-Cambrian areas exposed to-day commonly show abrupt changes from weak schistose belts into strong competent gneisses, and, presumably, the pre-Cambrian complex under the Paleozoic blanket of sediments in north-central Oklahoma would show a similar diversity of rock types, which would not be limited to any one direction.

From the foregoing considerations, it may be inferred that the pre-Cambrian basement in this area has two dissimilar characteristics: (a) north-northeast zones of weakness which may be due to structural or lithologic causes, and (b) resistant masses containing local weaker areas which show little definite alignment. Until the basement complex is better known, it is impossible to determine accurately what particular group of characteristics or conditions is present, especially since the pre-Cambrian topography also must be considered.

WHAT IS THE LOCAL EXPRESSION OF THE VERTICAL UPLIFTS?

The need of vertical stresses to explain adequately the origin of the structural features of north-central Oklahoma was early recognized by Gardner.² The gist of his theory is that

pressures are set up on the fluid rocks permitting hydraulic forces to act equally in all directions. At places where the total strength of overlying rocks is not competent to withstand this pressure there is a local folding of the whole mass. Such a structure may be very local in nature.

Such a conception of dominant vertical stresses does not explain all the types and details of failure found in the area, but, unfortunately, it has been judged on that basis, and, as a result, has been discarded by many *in toto*. However, a careful analysis of this pioneer contribution to the origin of the Mid-Continent structures reveals a broad grasp of

¹Rudolf Ruedemann, "The Existence and Configuration of Pre-Cambrian Continents," *New York State Museum Bull.* (1923), pp. 239-40.

²J. H. Gardner, "The Vertical Component in Local Folding," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 1 (1917), pp. 107-09.

the subject. Despite the criticism which the theory has received, the writers feel that *vertical stresses* merit further consideration.

A regional vertical stress acting upward on a pre-Cambrian complex having characteristics such as already outlined, would express itself differentially along zones and points of weakness. Especially would this be true if such a stress were continued through a long period of time, as time is necessary to permit local points of weakness to "give" and the stress to readjust itself so that the entire area will remain under the constant influence of the regional forces. It should be emphasized that if the weak point "gives" at all, even though the amount of deformation be extremely small, it will be repeated, and thus accentuated, as soon as the vertical stress builds up so as to approach equality with that in the surrounding area. In this way the deformation will continue as long as the regional stress is active, unless for any reason it becomes impotent. A periodic recurrence of the stress would act in a similar manner and should normally accentuate the previous deformation. Time would thus permit local adjustments and expressions of the relief of stress, which otherwise might give only a uniform regional failure.

It is impossible to say whether the upward deformation above a zone of weakness will be accomplished by bulging or faulting, but inasmuch as the rate of movement would perhaps be slow, bulging would probably be dominant. Since the formations above such an active zone would be in tension, a thinning of the beds due to stretching would be expected, and if the formations were not entirely consolidated, actual flowage away from the vertically stressed area would occur.¹ This folding should take place throughout the entire width of a *zone of weakness*, and vary in intensity as the weakness of the zone itself varied. Where the uplift is relatively intense, breaking would be probable and should express itself as upthrust normal faults; where there are pre-existing *lines of weakness*, faulting would be expected.

In general, then, small failures would not be due to any local isostatic adjustment, as it is manifestly illogical to use local differences of loading as the explanation for domes 1 square mile in area. Also, it should be emphasized that local igneous intrusions are not necessary as the uplifting force. In fact, isostatic adjustments of a regional character seemingly furnish the necessary vertical stresses, and their differential expression would result in many local surface failures.

¹For a further discussion of the effect of a rejuvenation, see C. M. Nevin and R. E. Sherrill, "Studies in Differential Compaction," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 1-22.

When local failures in the basement complex take place, the overlying blanket of sediments also must be deformed. Since these failures in the sediments are the result of a local upward thrust, they should show certain distinguishing characteristics, evidence of which would be expected.

One of the important types of structure in north-central Oklahoma is the small, almost circular dome. The total area affected is very small for the amount of vertical movement. The vertical extent is remarkable for the size of such domes. They do not die out downward, but increase in intensity with depth, especially beneath each unconformity. A distinct thinning of the section above the structure, in comparison with that off structure, is ordinarily present. The domes are numerous and really are more common than they at first seem, when it is remembered that the present regional dip has caused many to take the form of noses. Attempts have been made to connect them in definite alignments, but lines uniting them may be run in almost any desired direction. In reality they seem to have a haphazard arrangement.

It seems impossible to explain small domes with such characteristics as due to lateral stress, whether transmitted through the sediments or the basement complex. On the other hand, they are the natural result of local vertical stresses. At the risk of an unnecessary repetition, the writers wish to reiterate that they do not consider these vertical forces to be the result of local isostatic compensation, but believe them to be the local expression, at points of weakness in the basement complex, of regional uplifts.

There would seem to be no reason to doubt that a relatively small area of weakness will be deformed by regional stresses; hence, the small size of these domes does not make it less probable that they overlie small, relatively weak areas in the basement. Aside from differential compaction, what reasonable explanation, other than local vertical stresses, can be given for the small circular surface domes which continue downward and increase in intensity through all the unconformities?

The small, elongated, irregularly distributed domes and anticlines need little additional consideration. Though their elongation may suggest the operation of forces other than vertical stresses, they may also be the normal surface expression of regional uplifting forces acting on small elongated areas of weakness in the complex.

In contrast with these small, irregularly situated domes and anticlines are the large major structures trending north-northeast, which are especially well developed in the western part of the area. Many of these

are located along lines of weakness, such as the Blackwell anticline, the Ponca anticline, the Dexter anticline, and the Cushing failure. This alignment might appear to be the result of lateral stresses, but, since these folds are isolated in an area of relatively mild deformation, it was early recognized by Gardner¹ that vertical stresses were more probable. Gardner's theory, however, gave no explanation for the alignment, and this is one reason why that theory has not been generally accepted.

If it is admitted that the "grain of the continent" has given zones of weakness, such as fault and schistosity zones and lithologically weak belts, trending in a direction parallel with the alignment of these major failures, then it naturally follows that vertical stresses would result in deformation which would be guided by such zones. Other things being equal, the largest zones of weakness would give the largest structures with the greatest amount of closure. Under such conditions, the ordinary failure would probably be anticlinal bulging and would be controlled by a *zone* rather than a *line* of weakness, but because of the amount of uplift, faulting also would be expected. The common occurrence of abnormally steep dips associated with these large structures may indicate the presence of subsurface faults. The fact that the surface structures, along the line of anticlinal bulging, differ in their degree of deformation indicates that the underlying zone is not equally weak at all points. This is to be expected, and the character of the zone may change so completely that the overlying surface failure will rapidly disappear laterally, as seems to be the fact at Cushing.

Finally, upthrust normal faults have generally been considered the result of vertical stresses. The fault on the east side of the Nemaha Mountains is an excellent example. These buried mountains are in Kansas, but in their geologic history they are intimately related to north-central Oklahoma, as they lie along an extensive zone of weakness which trends in the prevailing north-northeast direction and probably extends south, at least as far as the Garber field in Oklahoma. Thomas² gives reasons for believing that their east face is a normal fault in which the west side moved up instead of the east side being depressed. An example of the same occurrence, on a small scale, is found in the Thomas field.³ This local faulting and the extensive failure in the Nemaha

¹J. H. Gardner, "The Mid-Continent Oil Fields," *Bull. Geol. Soc. Amer.*, Vol. 28 (1917), p. 719.

²C. R. Thomas, "Flank Production of the Nemaha Mountains," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1926), p. 926.

³S. K. Clark, "Thomas Oil Field, Kay County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 643-55.

Mountains occurred during the regional uplift near the close of the Mississippian, and seem best explained as local expressions of regional vertical stresses acting on a basement complex containing zones, lines, and points of weakness.

SUMMARY

It is an impressive fact that no single set of forces has been found adequate to explain all the structural features observed and recorded in north-central Oklahoma. Recognizing this fact, the writers have not intended to minimize the importance of any forces which are known to have been active in the area, but they feel that regional uplifts have not received the consideration they deserve; therefore, they have attempted to indicate the possible importance of such uplifts in the formation of local structures.

There are good reasons to assume that the basement complex contains intensive zones of weakness trending north-northeast, and also scattered points of weakness. Plentiful evidence indicates that regional vertical stresses have periodically acted upward on this basement. Under these conditions it would be surprising if the weak areas did not undergo a differential uplift. Many structures seem to indicate clearly that such local uplift did accompany the regional vertical stresses.

Finally, it is not desired to convey the idea that the effect of regional vertical stresses will be noticeable, or even present, in all local structures; but, as there is evidence to indicate that this effect has been of major importance in many places, would it not be well to reconsider vertical stresses and analyze carefully their possible local reflection?

ORIGIN OF THE EN ÉCHELON FAULTS IN NORTH-CENTRAL OKLAHOMA¹

R. E. SHERRILL²
Ithaca, N. Y.

ABSTRACT

That lateral slipping movements along buried faults, as postulated by Fath and accepted, with modifications, by others, are in reality the explanation of the *en échelon* faults of north-central Oklahoma seems improbable. It is difficult to accept the Ouachita thrust as the source of the stress necessary to cause such movements. Other sources of stress may be assumed, but the lack of continuity of the surface fault zones and the manner in which their trend swings with the strike of the Pennsylvanian formations make it difficult to believe that all of them follow pre-Pennsylvanian buried faults.

Torsion, augmented by a slight uplift, will give such *en échelon* faults, and by this combination of stresses such faults were formed experimentally. The field relations in north-central Oklahoma show that these stresses were active in a considerable part of the faulted area.

The peculiar characteristics of the numerous long and straight-line zones of *en échelon* normal faults in north-central Oklahoma have led to much discussion of their origin. An analysis of the suggestions which have been offered indicates that considerable doubt still remains as to their exact mode of formation. It is the purpose of the writer to call attention to another combination of stresses by which such *en échelon* breaks may be formed.

The fault zones, whose trends range from N. to N. 25° E., have been described by several writers³ and are well shown on the new areal geology map of Oklahoma published in 1926 by the United States Geological Survey. Most of the individual faults in any zone are approximately parallel and strike in a northwesterly direction. Few of them

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²Eleanor Tatum Long graduate scholar in structural geology, Cornell University. Present address, department of geology, University of Pittsburgh, Pittsburgh, Pennsylvania.

The writer is especially indebted to C. M. Nevin, assistant professor of structural geology, Cornell University, for his constructive criticisms and valuable suggestions.

Acknowledgment and thanks are also due A. I. Levorsen, chief geologist of the Independent Oil and Gas Company, K. C. Heald, of the National Research Council, and W. B. Wilson, of the Gypsy Oil Company, for their assistance in obtaining field data and for valuable criticism of the paper.

³See A. E. Fath, "The Origin of the Faults, Anticlines and Buried 'Granite Ridge' of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-C* (1920), pp. 75-84.

exceed 3 miles in length and most of them are nearer 1 mile. The throw, which is rarely more than 100 feet and generally nearer 50 feet, is commonly greatest near the center of the faults and diminishes toward the ends. The number of faults with the downthrow toward the southwest seems to be about the same as the number with the downthrow in the opposite direction. In most of the faults some rotational movement between the opposing walls is present, and in a considerable number this has been carried to such an extent that a pivotal fault has resulted.

The fault zones are best developed in Osage, Creek, Okfuskee, and Seminole counties, but they are present also in some of the adjoining counties. They do not seem to occur northward in the limestone section of Kansas; and, for the most part, the exposed strata in which they are known to occur consist of relatively brittle sandstone. In the southern part of the area they are present at the surface in beds as old as the Wewoka, but in the northern part of the area the oldest strata in which they seem to occur are considerably younger.

It is not definitely known whether the amount of throw increases or decreases downward, but most of the evidence indicates that the faults die out with depth — probably not extending below the Pennsylvanian formations.

Especially significant would seem to be the fact that, where developed, the fault zones are closely parallel with the strike of the outcropping Pennsylvanian strata, and the changes in the general direction of strike in different parts of the region are accompanied by corresponding changes in the direction of trend of the fault zones. Thus, in Lincoln County, where the strike of the outcropping strata is about N. 5° E., the fault trend is approximately parallel with it, and in Okfuskee County, where the strike has changed to about N. 25° E., the fault trends have made a corresponding swing. This relationship indicates that the faults were caused by the same forces which caused the present regional dip. Levorsen¹ suggests that they were formed at the time of this tilting.

Fath² offers an ingenious explanation for the origin of these faults by postulating horizontal movements along north and south lines of weakness in the pre-Cambrian complex. These lines of weakness supposedly underlie the fault zones, and, if the east side of a line of weakness moves north with respect to the west side, tears trending northwest and southeast are originated in the overlying sediments. Slump resulting

¹A. I. Levorsen, "Geology of Seminole County," *Oklahoma Geol. Survey Bull.* 40-BB (1928), p. 31.

²A. E. Fath, *op. cit.*

from these tears gives vertical displacements which are expressed at the surface as faults. Normal to the tension which results in the faults there would be a compressional element which should result in *en échelon* folds. Applying Fath's suggestion, Foley¹ obtained such folds and faults experimentally. Merritt and McDonald² agree with Fath in postulating movements in the basement, but believe that the throw of the faults would decrease downward rather than increase as supposed by Fath. They give a very complete explanation of the several types of folds that should normally be associated with faults formed by such horizontal movements below, and they consider that the Ouachita thrust gave the stress responsible for the slipping movements. Levorsen³ suggests that the original deformation, which occurred after the end of the Mississippian, was fundamentally a gravity-fault deformation and that the later westward tilting caused horizontal differential movements along these buried fault trends, which fractured the surface beds according to the mechanics of Fath and Foley.

In reviewing Fath's theory and the variations of it that have been suggested, several considerations seem to make it doubtful whether such lateral slipping movements actually occurred and are the explanation of the *en échelon* faults in this area.

In the first place, it is necessary for the east side of a line of weakness to move north with respect to the west side, and it also seems that the amount of movement would have to be approximately the same in all the faulted area because, actually, the faults are about equally well developed in all the affected area. This would seem to require that the subsurface lines of weakness should be continuous throughout the area, and that there should be a uniform stress acting from the south or southeast. Movements along such continuous lines of weakness should, then, give individual fault belts which would be correspondingly continuous. If the attempt is made to trace the *en échelon* fault zones through the area, it is seen that most of them lack continuity.

Furthermore, if we are to consider the Ouachita thrust as the southeast source of the stress which caused the slipping movements, the *en échelon* faults should be much more numerous or their displacement should be much greater in Seminole and Okfuskee counties than they are

¹Lyndon L. Foley, "Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 293-303.

²John W. Merritt and O. G. McDonald, "Oil and Gas in Creek County, Oklahoma," *Oklahoma Geol. Survey Bull. 40-C* (1926), pp. 12-35.

³A. I. Levorsen, *op. cit.*, pp. 28-39.

in Osage County, because the former counties are about 75 miles nearer the assumed source of stress. Such a general southward increase in the faults does not seem to be present. Then, too, it must be remembered that the principal thrust which is known to have occurred in the Ouachita region came in the latter part of Wewoka time¹—hence before the deposition of the present surface formations in which the faults are known to occur. Van der Gracht² states, however, that this deformation had a second phase which can not be timed because of the lack of beds younger than the Permian. There seems to be no positive evidence that this second thrust was comparable in magnitude with the earlier one. In a previous paper³ attention was called to evidence which indicates that the effect of the major thrust from the Ouachitas died out rapidly northward. If this be true, it would seem that the probability of a later thrust in this area resulting in deformation in regions more than 100 miles away should be regarded with considerable doubt. Objections to using the Ozarks as the source of the necessary thrust have been pointed out by Merritt and McDonald.⁴

On the other hand, the tilting which gave the present regional dip might have resulted in horizontal movements along buried faults, as suggested by Levorsen.⁵

Whether the lines of weakness are in the pre-Cambrian complex or in an upper horizon, if the *en échelon* faults are to be explained by lateral slipping along buried faults, it becomes necessary to assume that these subsurface faults are parallel with the strike of the outcropping strata and swing with it. Since these buried faults would be separated from the surface formations by one major unconformity or possibly more, such a parallelism would be a remarkable coincidence, or else it would indicate that the subsurface lines of weakness exerted a guiding influence on the forces which tilted the region. Such a directive effect might be considered were it not for the fact that the strike of the pre-Pennsylvanian

¹R. H. Dott, "Pennsylvanian Paleogeography," *Oklahoma Geol. Survey Bull.* 40-J (1927), p. 14.

²W. A. J. M. van Waterschoot van der Gracht, "Discussion on the Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 302.

³C. M. Nevins and R. E. Sherrill, "The Nature of Uplifts in North-Central Oklahoma and Their Local Expression," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 23-30.

⁴John W. Merritt and O. G. McDonald, *op. cit.*, p. 27.

⁵A. I. Levorsen, *op. cit.*

formations is generally widely divergent from the strike of the outcropping Pennsylvanian strata.

Finally, Powers¹ states

that the few faults which are known in the Ordovician do not offset the structure, and hence do not indicate the type of lateral movement postulated by Fath.

The general mechanics of Fath's theory is open to so many differing interpretations and variable applications that it is difficult, if not impossible, to prove or disprove without question that movements of the character postulated by him actually occurred and formed the *en échelon* faults of this region. That such movements would form *en échelon* faults seems very probable, but the considerations previously pointed out indicate that considerable doubt still remains whether these movements actually did occur and did form the faults of this area. For this reason an attempt was made to find another mechanism by which such *en échelon* faults may be formed.

POSSIBILITY OF FORMING EN ÉCHELON FAULTS BY ANOTHER COMBINATION OF STRESSES

If relatively brittle sedimentary beds are subjected to sufficient torsion, breaks will be formed. If the stresses are in a direction tending to move the northeast and southwest areas down, relative to the southeast and northwest parts, then a torsion or twisting is produced and the resulting breaks trend in a general northwesterly direction.

Moreover, if sedimentary beds are uplifted into north and south folds, there is a tendency to develop north and south tension cracks within this steepened area.

These facts suggest the possibility that some combination of these stresses would develop northwest breaks along north and south zones, and thus give *en échelon* faults.

Suppose that the twist itself is not carried to such an extent that the northwest breaks are developed, but that while the beds are in this state of torsion an uplift along a general north and south axis increases the stress. Only a component of this increase would be effective in the direction of stress due to twist. Such an increase might appear slight in itself, yet be sufficient to cause breaks in the general area where it is effective. These breaks should trend northwest due to the dominant guidance of the twist; and, as they would occur in the north and south

¹Sidney Powers, "Structural Geology of the Mid-Continent Region: A Field for Research," *Bull. Geol. Soc. Amer.*, Vol. 36 (1925), p. 392.

steepened area, they should appear as north and south trends of *en échelon* breaks.

Assuming these considerations to be true, an experimental attempt was made to apply such a combination of stresses to a brittle body. After several unsuccessful attempts with different substances, it became evident that it was necessary to use some plastic material with a brittle surface. As best satisfying these requirements, 16-mesh copper screen wire was coated with cake frosting. The cake frosting entered into the meshes of the screen wire and remained plastic underneath while the surface developed a brittle crust. As the wire was deformed the stresses were transmitted through the plastic layer to the brittle crust and there resulted in breaks.

To this apparatus the combination of stresses here outlined was applied, that is, a slow twist was accompanied or followed by a slight uplift of a part of the screen. As a result of this combination of stresses, *en échelon* northwest breaks occurred. An interesting and seemingly significant feature was observed in connection with these breaks: they did not extend entirely across the steepened part, nor were they confined to the area of maximum steepening. On the contrary, they appeared as series of short *en échelon* breaks in the general area of steepening. Thus a broad steepened area would have in and near it several separate series of breaks. In general, these series trended in the direction of steepening, that is, north and south, but there seemed to be a tendency to swing slightly from this direction toward the depressed northeast and southwest parts of the screen.

It might seem that to be effective, this combination of stresses would require a very delicate adjustment, but this was found to be far from true. While under torsion, north and south cracks were not formed along the steepened area unless this steepening was carried to an extreme. Where a slight twist, insufficient in itself to develop cracks, was increased by a steepening in a part of the area, the *en échelon* cracks developed as already outlined; thus, the adjustment did not have to be exceptionally delicate.

Sufficient data are not available to determine definitely whether or not the mechanics as here outlined is applicable to the *en échelon* faults in north-central Oklahoma. A consideration of the present attitude of the Pennsylvanian strata in this area clearly demonstrates, however, that the forces which gave the present regional dip exerted a torsional stress on the formations. In the southeastern part of the area, as in Okmulgee, Okfuskee, and Hughes counties, the regional dip — 60

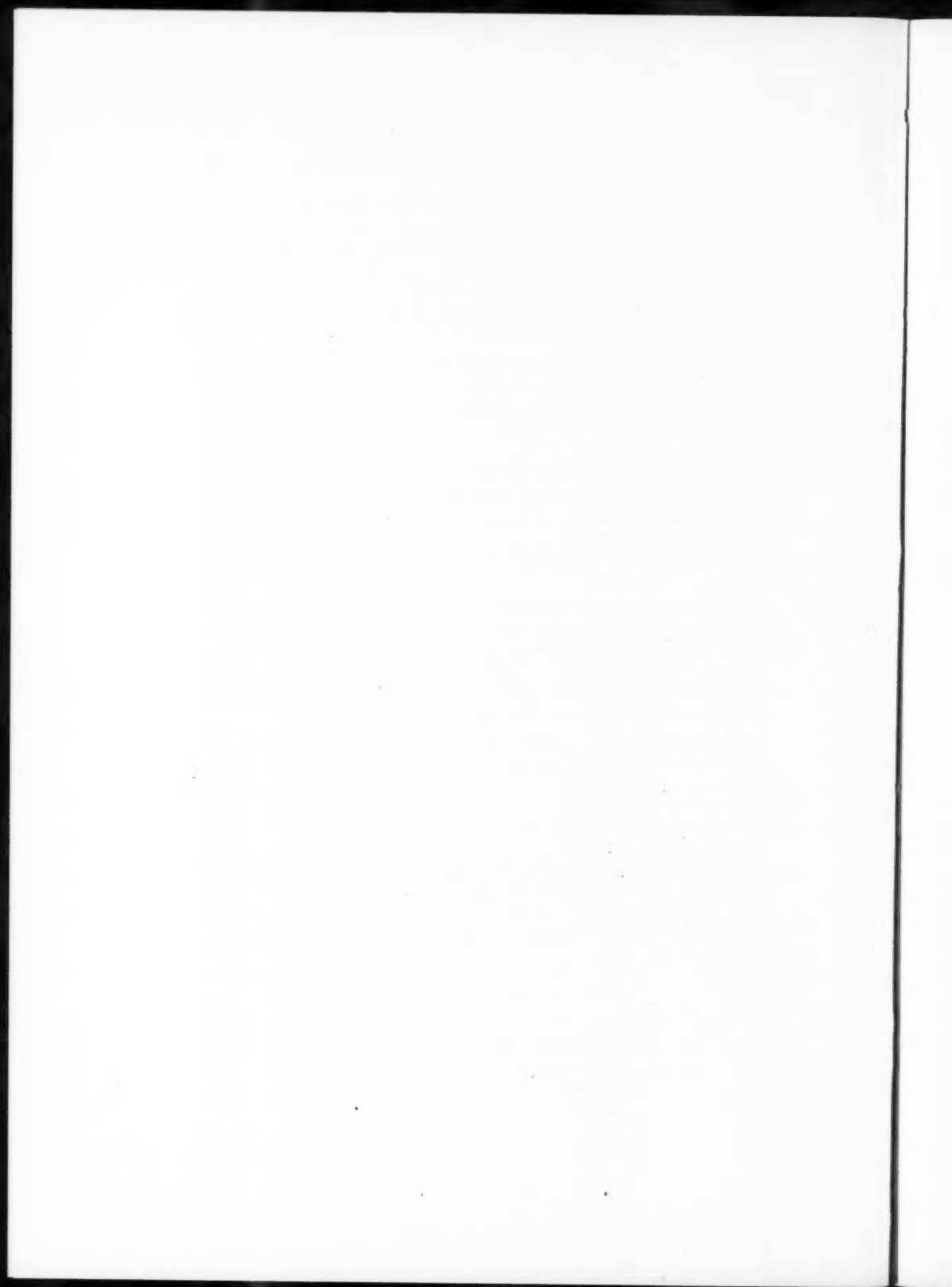
to 100 feet per mile — is much steeper than it is in the northeastern part of the area — 20 to 40 feet per mile in Washington, Rogers, and Nowata counties. This attitude of the formations shows that the southeastern part of the area had a relatively greater uplift than the northeastern part. In fact, this twisting is clearly indicated, on the areal map of Oklahoma, by the fan-like strike arrangement shown by the wider outcrops in the northeastern part.

Furthermore, in at least a considerable part of north-central Oklahoma, a general steepening of the regional dip of the surface formations in the general area of the *en échelon* faults is very noticeable. Thus, the average regional dip — as measured through distances approximating a township in width — is appreciably greater through central and eastern Osage County, where prominent fault zones exist, than it is west of this area in Kay and western Osage counties or east of the area in Washington and Nowata counties¹. A similar relationship exists in Creek County and the area east and west of it, but sufficient data are not available to show definitely that this condition exists in all places where the faults are present.

In general, then, it may be said that the present attitude of the surface formations in this area clearly indicates that they have been subjected to torsional stress and that in a part of the region this was accompanied or followed by a steepening of the regional dip in the faulted area. A combination of these stresses will, under proper conditions, form *en échelon* faults trending as do the faults in this area.

Finally, it might be suggested that we would normally expect *en échelon* faults formed by the combination of stresses as here outlined to be more numerous and better developed in the brittle sandstones, but they should also be present in the intervening shale layers, and they would probably die out with depth.

¹For regional dip data on these areas see: David White *et al.*, "Structure and Oil and Gas Resources of the Osage Reservation, Oklahoma," *U. S. Geol. Survey Bull.* 686; K. C. Heald, "Geologic Structure of the Northwestern Part of the Pawhuska Quadrangle, Oklahoma," *U. S. Geol. Survey Bull.* 691-C; C. W. Shannon and L. E. Trout, "Petroleum and Natural Gas in Oklahoma," *Oklahoma Geol. Survey Bull.* 19, Pt. II (1919); and E. Carpenter, "Geology of Washington County," *Oklahoma Geol. Survey Bull.* 40-V (1928).



A NEW GRAPHICAL METHOD FOR TORSION BALANCE- TOPOGRAPHIC CORRECTIONS AND INTERPRETATIONS¹

C. A. HEILAND²
Golden, Colorado

ABSTRACT

The graphical methods which have been suggested to date for the computation of topographic corrections and the effects of two- or three-dimensional geologic features involve mostly certain approximations. This makes it in many instances impossible to apply them to very steep topography or to abruptly changing subsurface structures. The approximations and the intricacies of the computations are due to the fact that either orthogonal or cylindrical coordinates are used. The author suggests a new method which is based on the use of spherical coordinates, the final formulæ of which are very simple and which does not involve approximations.

For sections made through any sort of terrain or subsurface structure in 16 azimuths, six diagrams are required. The construction of these diagrams is described. They are applicable (1) to the computation of topographic corrections and of corrections for mine openings in underground torsion-balance work; (2) to computations of the influence of two- and three-dimensional subterranean features in torsion-balance interpretation; (3) to computations of the influence of such structures on the magnetometer.

In a previous publication,³ the writer has emphasized the necessity of using topographic corrections for the Eötvös torsion balance which are not confined to definite radii. In the same publication, a method was suggested which is applicable to any distances; therefore, to any topographic conditions which show much irregularity in a horizontal direction. This advantage, that the leveling is not confined to definite distances, could be obtained by certain assumptions about the variation of height in the mass elements.

As pointed out in this paper, such analytical methods are not the only ones that are applicable to the computation of terrain effects. There are also graphical methods, the advantage of which is not only that they are more expeditious than the analytical methods, but that they also control automatically the accuracy with which any topographic effect may be computed.

The principle of such graphical methods was first suggested by B.

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²Professor of geophysics, Colorado School of Mines.

³C. A. Heiland, "A Cartographic Correction for the Eötvös Torsion Balance," *Amer. Inst. Min. Met. Eng. Tech. Pub. 52* (New York, February, 1928).

Numerov.¹ It may readily be understood from the following considerations.

Let us assume a vertical section through a horizontal stratum which is cut off at one end and infinite at the other. It is also infinite in either direction perpendicular to the section. We can divide this slab into several blocks. Computing the influence of these individual blocks on the torsion balance, we notice that their influence decreases as their distance increases. If the block closest to the instrument has, for instance, the effect of five Eötvös units on the gradient of gravity, we can compute another block adjoining the first that also produces the same effect, the length of which, however, is greater. In other words, we may subdivide the whole vertical section into blocks each of which produces a constant effect on the instrument, the dimensions of which, however, increase as their distance from the instrument increases. Thus, a diagram (Fig. 1) is obtained with the outlines of these blocks, a "graticule," which is preferably drawn on tracing cloth and placed upon a section of the geologic structure. The effect of the masses which build up this structure is then obtained by simply counting the number of elements that fall within the outlines of the individual masses.

In outlining the principle of his graphical method, B. Numerov described primarily two possibilities: (1) the use of vertical graticules for sections through structures (Fig. 1), and (2) horizontal graticules for topographic and subterranean effects, where the elevations are small as compared with distance (Fig. 2 and Fig. 3).

The idea of using a horizontal graticule has been taken up and further perfected by several other authors, for example, P. Nikiforov,² K. Jung,³ and E. Lancaster-Jones.⁴ Recently B. Numerov⁵ has given a detailed account of this method and has published several diagrams.

The principle of application of these horizontal graticules is as follows. The horizontal plane around the station is subdivided by radial

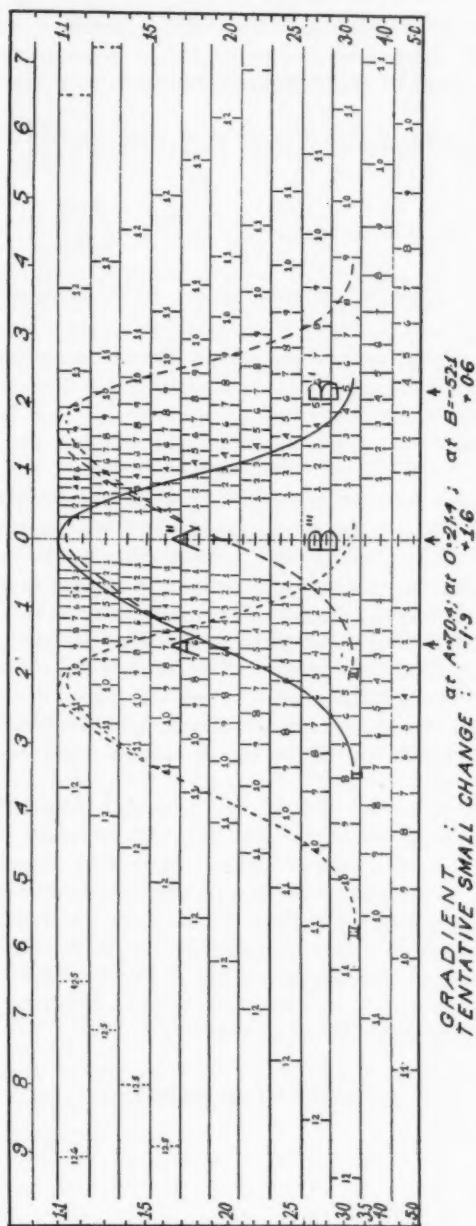
¹B. Numerov, "Graphische Methode zur Berücksichtigung des topographischen Einflusses und des Einflusses der unterirdischen Massen auf die gravimetrischen Beobachtungen," *Zeitschrift für Geophysik* (1924-25), Heft 8, Seite 367-71.

²P. Nikiforov, "Physical Principles of the Gravitational Method of Prospecting," *Institute of Practical Geophysics Bull. 1 and 2* (Leningrad, 1925 and 1926).

³K. Jung, "Diagramme zur Bestimmung der Terrainwirkung für Pendel und Drehwage und zur Bestimmung der Wirkung 'zweidimensionaler' Massen anordnungen," *Zeitschrift für Geophysik* (1927), Heft 5, Seite 201-12.

⁴E. Lancaster-Jones, "The Computation of Eötvös Gravity Effects," *Amer. Inst. Min. Met. Eng. Tech. Pub. 75* (New York, March, 1928).

⁵B. Numerov, "Die topographische Reduction bei Drehwagenbeobachtungen," *Zeitschrift für Geophysik*, Heft 3 (1928), Seite 117-34.



lines and concentric circles into sectors of differing magnitude, so chosen that the effect of a prism of constant height of which the sector is the base is the same for all prisms. The effects of any masses on the torsion balance

vary as the cosine of the azimuth for the north gradient $\left(\frac{\partial^2 U}{\partial x \partial z} = U_{xz} \right)$,

as the sine of the azimuth for the east gradient $\left(\frac{\partial^2 U}{\partial y \partial z} = U_{yz} \right)$, as

the cosine of the double azimuth for the north curvature value

$\left(\frac{\partial^2 U}{\partial y^2} - \frac{\partial^2 U}{\partial x^2} = U_{\Delta} \right)$, and as the sine of the double azimuth for

the east curvature $\left(2 \frac{\partial^2 U}{\partial x \partial y} = 2U_{xy} \right)$.

Hence, if we draw a graticule for U_{xz} , it follows that the sectors must be small and close together in the north and south and far apart in the east and west. If we draw a graticule for U_{yz} , the elements will be small and close together in the east and west and far apart in the north and south. It is, therefore, not necessary to use two different graticules for U_{xz} and U_{yz} ; we can merely rotate the U_{xz} graticule through 90° to use it for U_{yz} . For the curvature values, the elements will be close together in the north, east, south, and west directions and far apart and greater in the intermediate azimuths. One diagram is here also sufficient for both U_{Δ} and $2U_{xy}$, as the diagram for the former may be rotated through 45° (Fig. 2 and Fig. 3).

Therefore, if $\alpha_0, \alpha_1, \alpha_2 \dots \alpha_m$ are the azimuths of the radial lines which separate the individual elements, they are so spaced that

$$\sin \alpha_{m+1} - \sin \alpha_m = \text{constant for the gradient diagram}$$

and $\sin 2\alpha_{m+1} - \sin 2\alpha_m = \text{constant for the curvature diagram.}$

The datum which defines the size of the elementary sectors in the second dimension is the distance of consecutive concentric circles. The width of these rings must naturally increase as the distance of the elements from the station. B. Numerov and E. Lancaster-Jones assume the following relationship of subsequent radii:

$$\frac{1}{\rho_{n+1}^2} - \frac{1}{\rho_n^2} = \text{constant for the gradients}$$

and

$$\frac{I}{\rho} - \frac{I}{\rho_{n+1}} = \text{constant for curvature values}$$

K. Jung, however, makes use of the same law for both gradients and curvature values, namely

$$\log_e \frac{\rho_{n+1}}{\rho_n} = \text{constant}$$

The third dimension, or the elevation of the topography, is taken into consideration by K. Jung by substituting the angle ϵ under which the elevation appears as seen from the station. The factor with which he has to multiply the effect of the elementary sector is, consequently, a more or less involved trigonometric function of this angle ($1 - \cos^3 \epsilon$ for gradients and $3 \sin^3 \epsilon - \sin^3 \epsilon$ for curvatures) which functions may be taken from diagrams which he has constructed for this purpose. In addition, it is necessary to draw lines of equal angle of elevation for the terrain under investigation. All this complicates matters to some extent; however, the method is rigorous.

Another method proposed by B. Numerov for the consideration of the third dimension with horizontal graticules is not rigorous, but much easier in application than Jung's method. In case the elevations are small compared with their distance, the integration over the vertical ordinate of the masses may be confined to the first terms of the expansion in series. Thus the factors with which the effects of the individual sectors must be multiplied are simpler than in Jung's method. The application of the diagram shown in Figure 1 of Numerov's last article¹ is, consequently, as follows, if a contour map of the terrain or subsurface structure is available (Fig. 3). The diagram (preferably drawn on tracing cloth) is placed on the contour map. The area within two consecutive contours is always considered at the same time, and the sectors are counted that fall within these two lines. Their number is multiplied by the average " h " of the elevations represented by the two contours, if the influence on curvature values is to be determined. For the gradients, another diagram must be used (Fig. 2); then the factor is not h , but

$\zeta h - \frac{I}{2} h^2$, ζ being the elevation of the instrument above the ground. The

result is to be multiplied by the density, if the same is uniform all around the station; if not, the individual sectors must be multiplied by

¹B. Numerov, *op. cit.*, p. 132.

their respective density. For subterranean structures $-h$ must be substituted for $+h$ in the factors here given; instead of the density, the difference in density between structure and adjacent formation must be used.

This method is especially applicable for topographic features and any irregular subsurface structures such as domes, anticlines, and granite ridges, for which contour maps are available, if the slopes are not too steep.

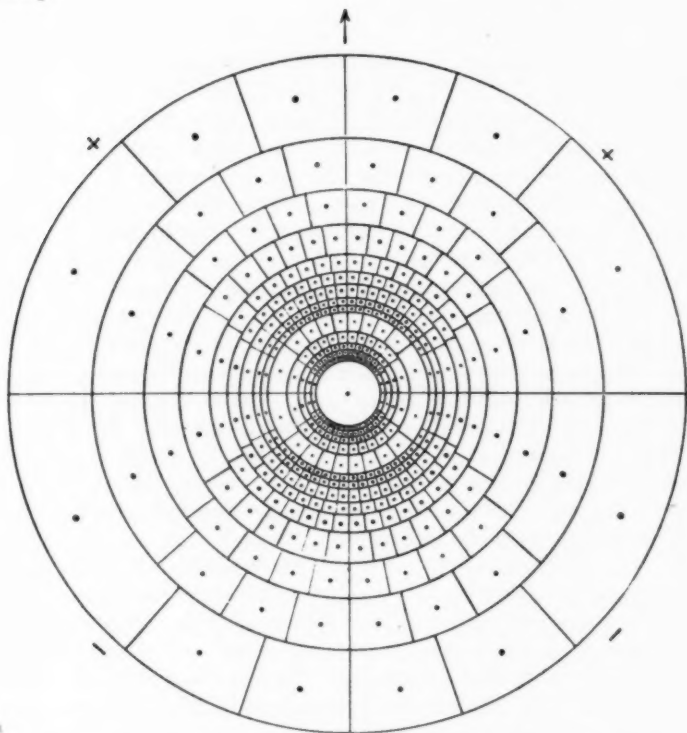


FIG. 2.—Horizontal graticule for the computation of the influence of the topographic or subterranean relief on the gradients of gravity. To be used with contours from 50 to 500 arbitrary linear scale units. Unit effect of elements in the first 5 rings: $1 \cdot 10^{-12}$ C. G. S.; unit effect of the remainder: $1 \cdot 10^{-13}$ C. G. S. Density: 1. If arrow is oriented toward the north (for U_{xz}) or toward the east (for U_{yz}), the signs indicate the effects of masses below the horizon (earth's surface) on U_{xz} and U_{yz} , respectively. For masses above the horizon, the change in sign is made by applying (if $h > 2\frac{1}{2}$) the formula given on page 43. For terrain corrections, the negative effect is taken. After Numerov.

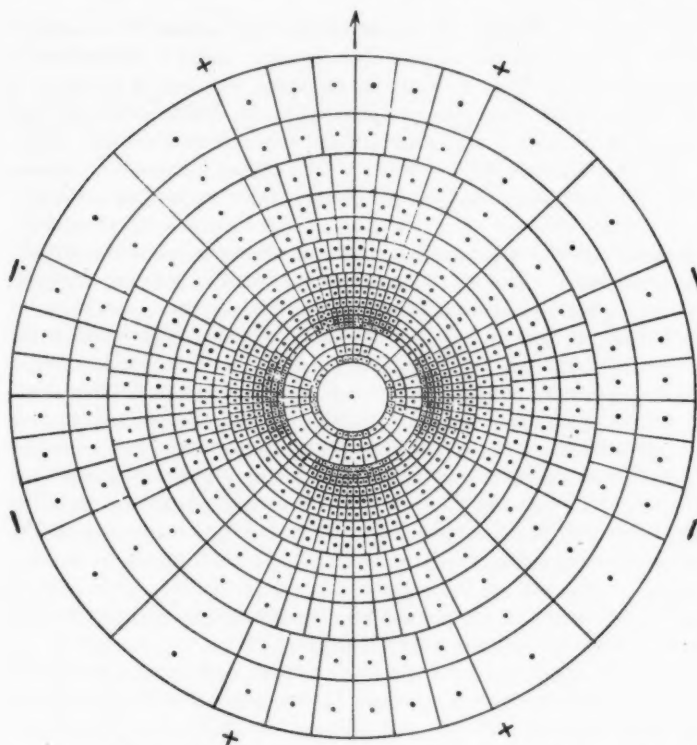


FIG. 3.—Horizontal graticule for the computation of the influence of the topographic or subterranean relief on the curvature values. To be used with contours from 50 to 500 arbitrary linear scale units. Unit effect of the elements in the first 3 rings: $1 \cdot 10^{-10}$ C. G. S. Unit effect of the remainder: $1 \cdot 10^{-11}$ C. G. S. Density: 1. If arrow is oriented toward the north (for U_{Δ}) or northeast (for $2 U_{xy}$), the signs indicate the effects of the masses above or below the horizon on $-U_{\Delta}$ and $2U_{xy}$, respectively. For terrain corrections, the negative effect is taken. After Numerov.

If the slopes are steep, however, it seems to be better to choose the second type of graphical methods, as suggested by B. Numerov, namely, vertical graticules. Vertical graticules are very suitable for the evaluation of vertical cross sections of subsurface structures at right angles to their strike, provided that their extent in the strike on either side of the section is virtually infinite. The first to make use of B. Numerov's suggestion was D. C. Barton,¹ who published diagrams for such infinite

¹D. C. Barton, "Calculations in the Interpretations of Observations with the Eötös Torsion Balance," *Amer. Inst. Min. Met. Eng. Tech. Pub.* (New York, 1928).

structures. He attempted also to modify this method for structures which are finite in the strike. This, however, leads to difficulties, as for any one structure (a dome, for example) the ratio of thickness to the length of the mass elements changes as the depth. The diagrams obtainable for such finite lengths of the elements in the strike permit only an approximate determination of their effects, because it is impossible to construct diagrams for *all* the possible ratios of thickness to length.

It occurred to the writer, therefore, that it may be best, in the analysis of such three-dimensional structures, to use several vertical graticules in several sections through the structure, for example, in the north-south, east-west, northeast-southwest, and northwest-southeast directions, or better still, in these and the intermediate directions. The extent of the masses on either side of the sections would always be constant or 22.5° for four and 11.25° for eight sections. It was desired to make this method rigorous as well as rapid and practicable; therefore, the following method was worked out. In view of the fact that the integration with respect to "*h*," that is, the use of cylindrical coördinates, always involves an approximation, it was decided to abandon cylindrical coördinates altogether and to use spherical coördinates. This new method requires eight diagrams (corresponding to sixteen azimuths; each diagram to be constructed twice, for gradients and for curvature values). However, it will be seen later that of these sixteen diagrams, ten are alike, so that the construction of only six diagrams is required.

Before this manuscript could be completed, there appeared an article by H. Haalck¹ in which he also uses vertical graticules for three-dimensional structures. Although it is claimed that this method is rigorous, this is not entirely the fact. The approximation consists in a substitution of a rectangle for the rhomboid that is formed by two parallel vertical lines and two sides of an angle.² Thus the center of gravity is displaced from its original position; though the error is small, it may become noticeable under less favorable circumstances.

H. Haalck computes diagrams for only one azimuth. The same diagrams must be used for all other azimuths of the other cross sections through the structure or through the terrain. If n_1 is the number of elements of the diagram comprised by the outline of the structure in azimuth No. 1, n_2 the number of elements comprised by the section in azimuth No. 2, and so on, then it is necessary to apply the following

¹H. Haalck, "Ein graphisches Verfahren für Drehwagenmessungen zur Berechnung der Gelaendewirkung und der Wirkung beliebig gestalteter Massenkoerper," *Zeitschrift für Geophysik* (1928) Heft 4, Seite 161-78.

²H. Haalck, *op. cit.*, Seite 166.

formulæ in addition to counting elements. For example, for U_{zz} and for sixteen azimuths:

$$U_{zz} = -2C \cdot \sin 11.25^\circ \left\{ \begin{array}{l} -n_8 + n_{16} + \cos 22.5^\circ (n_1 + n_{15} - n_7 - n_9) \\ + \cos 45^\circ (n_2 + n_{14} - n_6 - n_{10}) \\ + \cos 67.5^\circ (n_3 + n_{13} - n_5 - n_{11}) \end{array} \right\}$$

H. Haalck has chosen this arrangement because he believes that it is advisable to have as few diagrams as possible.

This does not seem in accordance with the general view of many practical operators of the torsion-balance method. The graphical method is one step further toward a routine correction, that is, a correction the computation of which may be entrusted to a man who has neither mathematical ability nor much skill in handling numerical calculations. If we apply a graphic method with such conversion formulæ as here given, it will probably be impossible to have the computation made by men who are not thoroughly trained. The mere counting of elements, however, can be done satisfactorily by a less expert calculator. It seems much better, therefore, to figure once for all eight diagrams for sixteen azimuths or four diagrams for eight azimuths, for both gradients and curvatures, so that the remainder of the computation may be done by less skilled men. Another advantage of this procedure is the saving of time. The computation of the diagrams need be done only once, while the application of them will probably be made a thousand times or more. Furthermore, it is very easy to compute the graticules for any other azimuth after the graticule for the first azimuth is computed.

After these introductory remarks, the object of the following is to give the mathematical fundamentals for the computation of such graticules as are characterized in the last paragraph for terrain and three-dimensional structures. The coördinates used are spherical instead of cylindrical. Thus the final equations are both rigorous and simple.

A great advantage of the following method over most of the others is that the xy plane of our system passes through the center of gravity of the balance system and not through the point of set-up on the ground. Thus the distance of the center of gravity from the ground cancels out and the graticules are, consequently, applicable to any height of the instrument above the ground.

In a strict sense, the selection of eight or sixteen equidistant azimuths for the vertical graticules is not in accordance with the fundamental principle of the graphical correction, if we recall the distribution of the elementary sectors in a horizontal plane as described on page 42. In

order to attain the maximum possible accuracy, it would be necessary to draw cross sections through the structure, the azimuth of which would be in accordance with the relations given on page 42.

The sections would have to be made in the azimuths indicated by the dots in Figure 2 and Figure 3 in a definite distance, for example, in N. 6.5° E., N. 22° E., N. 39° E., N. 69° E., etc., for gradients, and in N. 2.5° E., N. 8.5° E., N. 15° E., N. 36° E. for curvature values.

This procedure, though very exact, seems to be impracticable.

For most practical purposes it is sufficient to work up eight graticules (corresponding to a terrain correction of sixteen azimuths), and use them for eight cross sections through the structure. Each graticule must be adapted to gradients and curvature values. With the sixteen diagrams thus obtained, of which ten are alike, as noted before, almost any practical terrain correction or structure effect can be computed. The scale of the diagrams to be described is altogether arbitrary. The chief requirement is that vertical and horizontal scales be equal. The same diagram may then be used, for example, for distances from 1 meter to 100 meters, or 100 meters to 10 kilometers. One graticule with but a few elements can thus cover a large territory through repeated application.

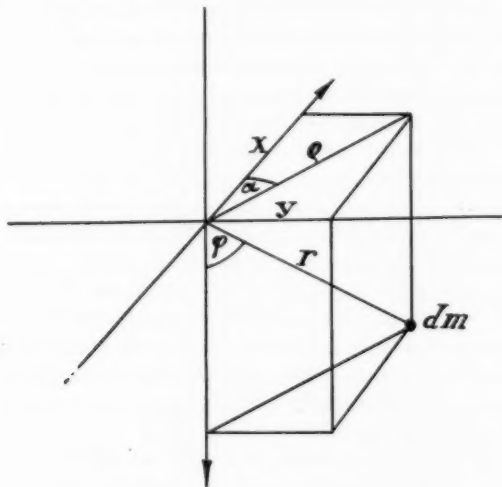


FIG. 4. Diagram showing coordinates of mass element.

The following are the mathematical fundamentals of a new graphical method that uses spherical coördinates.

Let us assume a point-shaped mass element dm (Fig. 4) in the distance r from the o -point of our system of coördinates, this zero point to be the center of gravity of the balance system; x , y , and z are the rectangular coördinates of dm , or

$$r = \sqrt{x^2 + y^2 + z^2}$$

The gravitational potential of this element is

$$U = k \int \frac{dm}{r} \quad (1)$$

where k is the gravitational constant. The second derivatives of U as used in torsion-balance work are, as derived from equation (1),

$$\left. \begin{aligned} \frac{\partial^2 U}{\partial x \partial z} &= U_{xz} = 3k \int dm \frac{xz}{r^5} \\ \frac{\partial^2 U}{\partial y \partial z} &= U_{yz} = 3k \int dm \frac{yz}{r^5} \\ \frac{\partial^2 U}{\partial y^2} - \frac{\partial^2 U}{\partial x^2} &= U_{\Delta} = 3k \int dm \frac{y^2 - x^2}{r^5} \\ \frac{\partial^2 U}{\partial x \partial y} &= U_{xy} = 3k \int dm \frac{xy}{r^5} \end{aligned} \right\} \quad (2)$$

In most graphical methods, cylindrical coördinates are used and the horizontal distance ρ of the element dm , or

$$\rho \cos \alpha = x \quad \text{and} \quad \rho \sin \alpha = y.$$

Substituting for ρ : $r \sin \varphi$, we have

$$r \sin \varphi \cos \alpha = x, \quad r \sin \varphi \sin \alpha = y \quad \text{and} \quad z = r \cos \varphi$$

so that equations (2) become

$$\left. \begin{aligned} U_{xz} &= 3k \int dm \frac{\sin \varphi \cos \varphi \cos \alpha}{r^3} \\ U_{yz} &= 3k \int dm \frac{\sin \varphi \cos \varphi \sin \alpha}{r^3} \\ U_{\Delta} &= 3k \int dm \frac{\sin^2 \varphi (\sin^2 \alpha - \cos^2 \alpha)}{r^3} \\ U_{xy} &= 3k \int dm \frac{\sin^2 \varphi \sin \alpha \cos \alpha}{r^3} \end{aligned} \right\} \quad (3)$$

or

$$\begin{aligned} U_{\Delta} &= -3k \int dm \frac{\sin^2 \varphi \cos 2\alpha}{r^3} \\ 2U_{xy} &= 3k \int dm \frac{\sin^2 \varphi \sin 2\alpha}{r^3} \end{aligned}$$

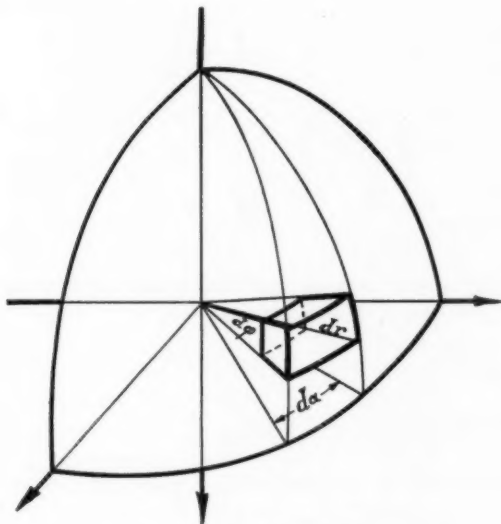


FIG. 5. Diagram illustrating spherical mass element.

These equations contain spherical coördinates only, radius (r), longitude (α), and latitude (φ).

For dm , we now take an element of a spherical shell, bounded by the surfaces of two concentric spheres the difference in radius of which is dr , by the sides of the differential longitude angle $d\alpha$ and by the sides of the differential latitude angle $d\varphi$ (Fig. 5). Then, σ being the density,

$$dm = \sigma \cdot dr \cdot r d\varphi \cdot r \sin \varphi d\alpha = \sigma r^2 \sin \varphi d\varphi dr d\alpha \quad (4)$$

We substitute this result in equation (3) and obtain for one graticule which is assumed to pass through the middle of the angle ($\alpha_{m+1} - \alpha_m$):

$$\left. \begin{aligned} U_{xz} &= 3k\sigma \int_{\alpha_m}^{\alpha_{m+1}} \int_0^{2\pi} \int_0^{\infty} \frac{\cos \alpha d\alpha \sin^3 \varphi \cos \varphi d\varphi dr}{r} \\ U_{yz} &= 3k\sigma \int_{\alpha_m}^{\alpha_{m+1}} \int_0^{2\pi} \int_0^{\infty} \frac{\sin \alpha d\alpha \sin^3 \varphi \cos \varphi d\varphi dr}{r} \\ U_{\Delta} &= 3k\sigma \int_{\alpha_m}^{\alpha_{m+1}} \int_0^{2\pi} \int_0^{\infty} \frac{\cos 2\alpha d\alpha \sin^3 \varphi d\varphi dr}{r} \\ 2U_{xy} &= 3k\sigma \int_{\alpha_m}^{\alpha_{m+1}} \int_0^{2\pi} \int_0^{\infty} \frac{\sin 2\alpha d\alpha \sin^3 \varphi d\varphi dr}{r} \end{aligned} \right\} (5)$$

Carrying out the integration with respect to α , we obtain the effect of the entire graticule which extends in either direction toward the sides of the angle $\Delta\alpha = \alpha_{m+1} - \alpha_m$, or

$$\left. \begin{aligned}
 U_{xz} &= 3k\sigma (\sin \alpha_{m+1} - \sin \alpha_m) \int_0^{2\pi} \int_0^\infty \frac{\sin^2 \varphi \cos \varphi \, d\varphi \, dr}{r} \\
 U_{yz} &= -3k\sigma (\cos \alpha_{m+1} - \cos \alpha_m) \int_0^{2\pi} \int_0^\infty \frac{\sin^2 \varphi \cos \varphi \, d\varphi \, dr}{r} \\
 U_\Delta &= -\frac{3}{2}k\sigma (\sin 2\alpha_{m+1} - \sin 2\alpha_m) \int_0^{2\pi} \int_0^\infty \frac{\sin^3 \varphi \, d\varphi \, dr}{r} \\
 2U_{xy} &= -\frac{3}{2}k\sigma (\cos 2\alpha_{m+1} - \cos 2\alpha_m) \int_0^{2\pi} \int_0^\infty \frac{\sin^3 \varphi \, d\varphi \, dr}{r}
 \end{aligned} \right\} (6)$$

The following numerical values must be substituted in these formulae for eight graticules:

TABLE I

Graticule No.	Azimuth of Section	U_{xz}		U_Δ	
		α_m	α_{m+1}	$2\alpha_m$	$2\alpha_{m+1}$
I	11.25°	0.00°	22.50°	0°	45°
II	33.75°	22.50°	45.00°	45°	90°
III	56.25°	45.00°	67.50°	90°	135°
IV	78.75°	67.50°	90.00°	135°	180°
V	101.25°	90.00°	112.50°	180°	225°
VI	123.75°	112.50°	135.00°	225°	270°
VII	146.25°	135.00°	157.50°	270°	315°
VIII	168.75°	157.50°	180.00°	315°	360°

From formulae (6) it is noted that

$$\cos \alpha_{m+1} - \cos \alpha_m = \sin (90^\circ + \alpha_{m+1}) - \sin (90^\circ + \alpha_m)$$

and

$$\cos 2\alpha_{m+1} - \cos 2\alpha_m = \sin 2(45^\circ + \alpha_{m+1}) - \sin 2(45^\circ + \alpha_m)$$

Hence, it is not necessary to construct graticules for U_{yz} and $2U_{xy}$, as mentioned before. In order to compute the effect of any topography

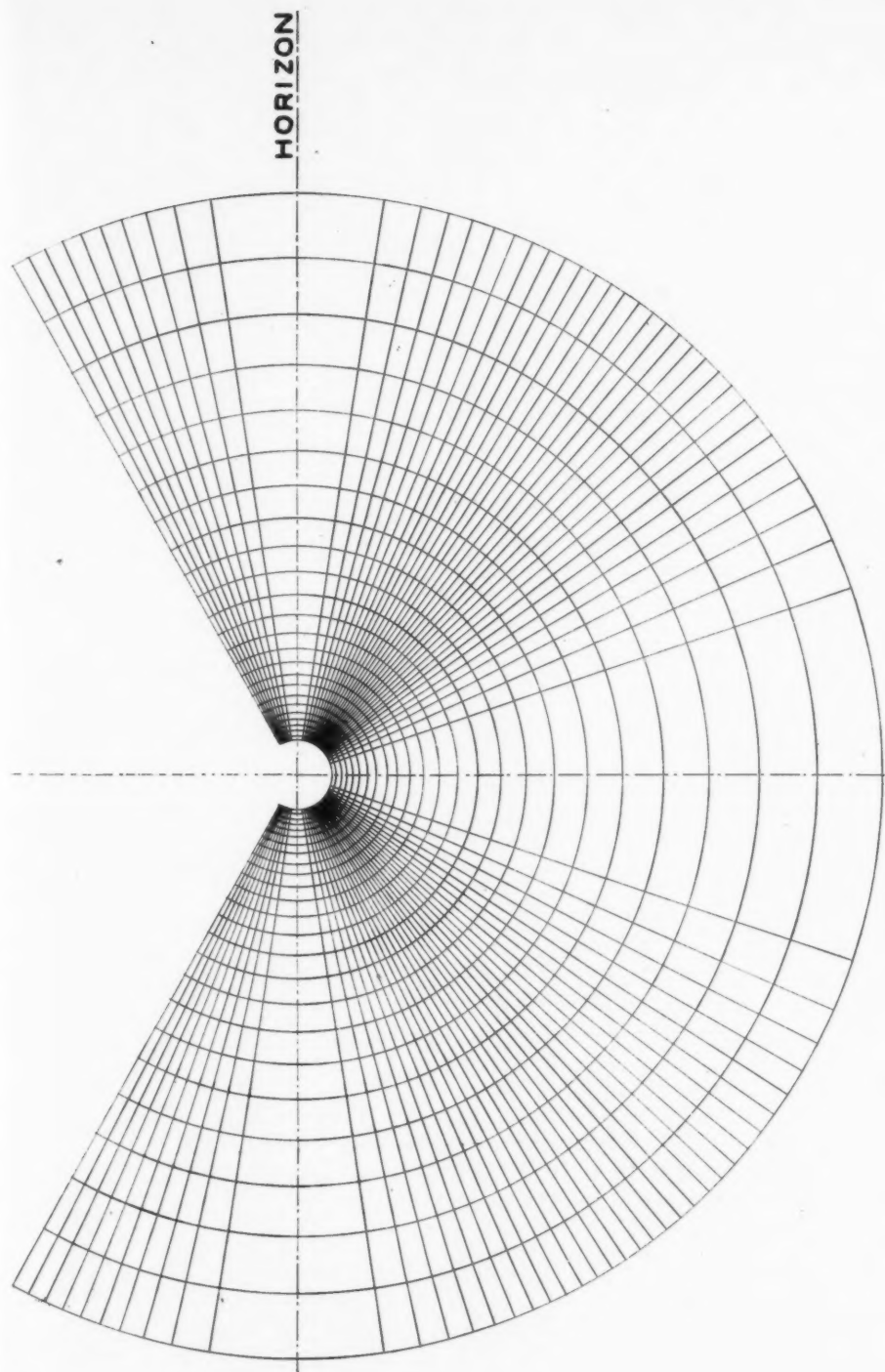


FIG. 6.—Gradient graticule *GI*. Density, 1. Unit effect, 1.10 to C. G. S.

or subsurface structure on U_{yz} and $2U_{xy}$, the graticules for U_{xz} and U_{Δ} are used. Graticule No. 1 for U_{xz} is then, for example, placed upon the cross section through the terrain or structure in the azimuth 101.25° , not 11.25° , and the graticule No. 1 for U_{Δ} on the section made in the azimuth 56.25° , so that a scheme is being applied which is illustrated in Figure 12.

From the diagrams shown in Figure 12 it is seen that eight graticules for gradients and eight graticules for curvatures are not necessary. For, if we denote for the various graticules I, II, etc.,

$$\left. \begin{aligned} \sin \alpha_{m+i} - \sin \alpha_m &\text{ by } (G)_I, (G)_{II}, \text{ etc., and} \\ \sin 2\alpha_{m+i} - \sin 2\alpha_m &\text{ by } (C)_I, (C)_{II}, \text{ etc.} \end{aligned} \right\} \quad (6a)$$

we will find after substituting for α_m :

$0^\circ, 22.50^\circ, 45^\circ, 67.50^\circ, 90^\circ, 112.50^\circ$, etc., and for α_{m+i} :

$22.50^\circ, 45^\circ, 67.50^\circ, 90^\circ, 112.50^\circ, 135^\circ$, etc., that

$$(G)_I = - (G)_{VIII}, (G)_{II} = - (G)_{VII},$$

$$(G)_{III} = - (G)_{VI}, (G)_{IV} = - (G)_V.$$

For gradients, therefore, the eight graticules reduce to four.

As to curvatures, we find by substituting the angles previously given that

$$(C)_I = (C)_{VIII} \quad (C)_{II} = (C)_{VII}$$

$$(C)_{III} = (C)_{VI} \quad (C)_{IV} = (C)_V$$

$$(C)_I = -(C)_{IV} \quad (C)_{II} = -(C)_{III}$$

$$(C)_I = -(C)_V \quad (C)_{II} = -(C)_{VI}$$

Hence, for curvatures, the eight graticules are reduced to two.

For both gradients and curvature, therefore, only six graticules are necessary instead of sixteen.

From formulae (6) it is seen that the size of the mass elements in each graticule depends upon their azimuth.

The question now arises how these elements are to be computed. For this purpose it is first necessary to determine the effect of each element. The cross section of such an element in the graticule is given by an area which is bounded by two concentric circles with the radii r_n and

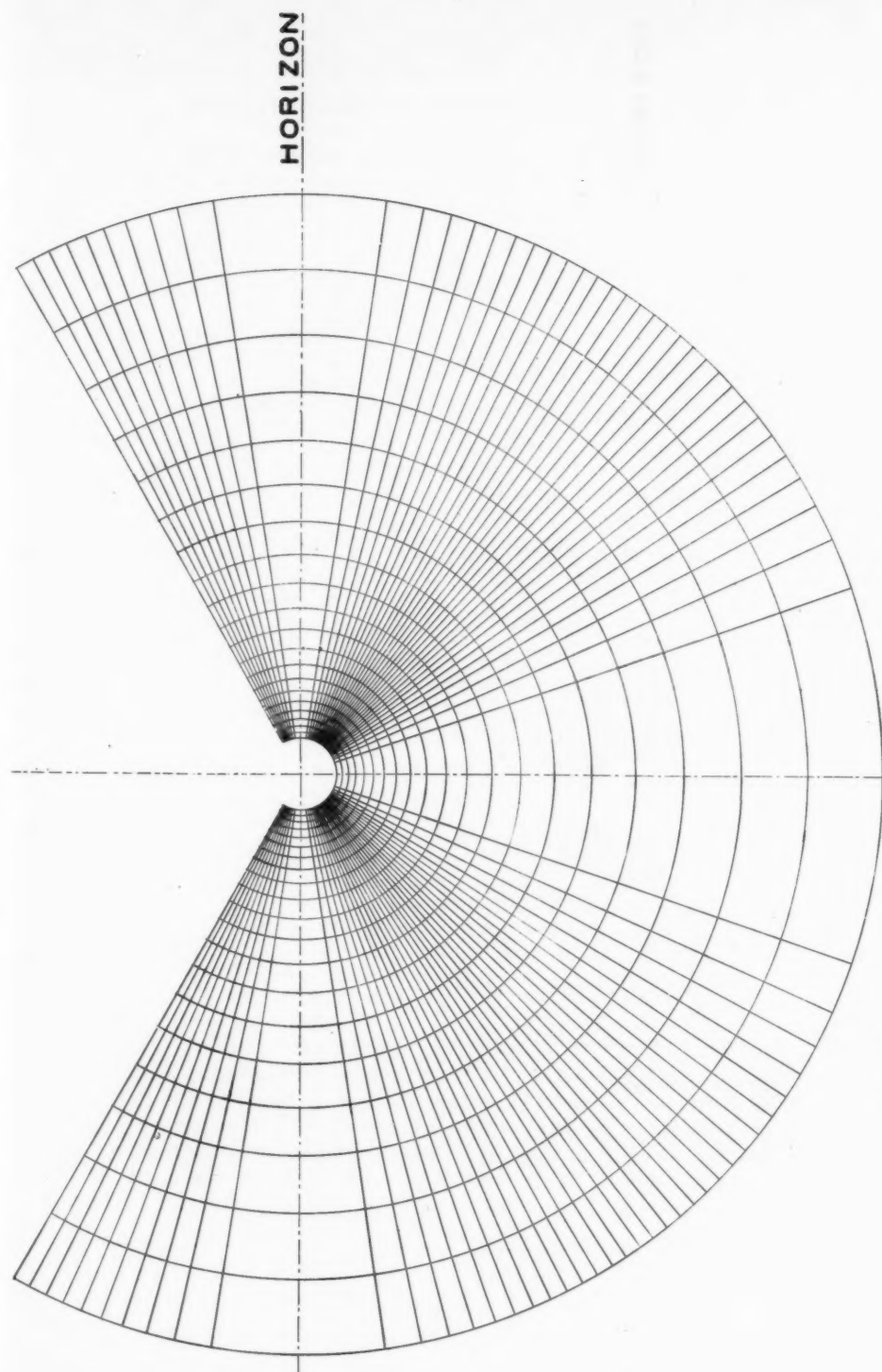


FIG. 7.—Gradient graticule *G II*. Density, 1. Unit effect, 1.10^{10} C. G. S.

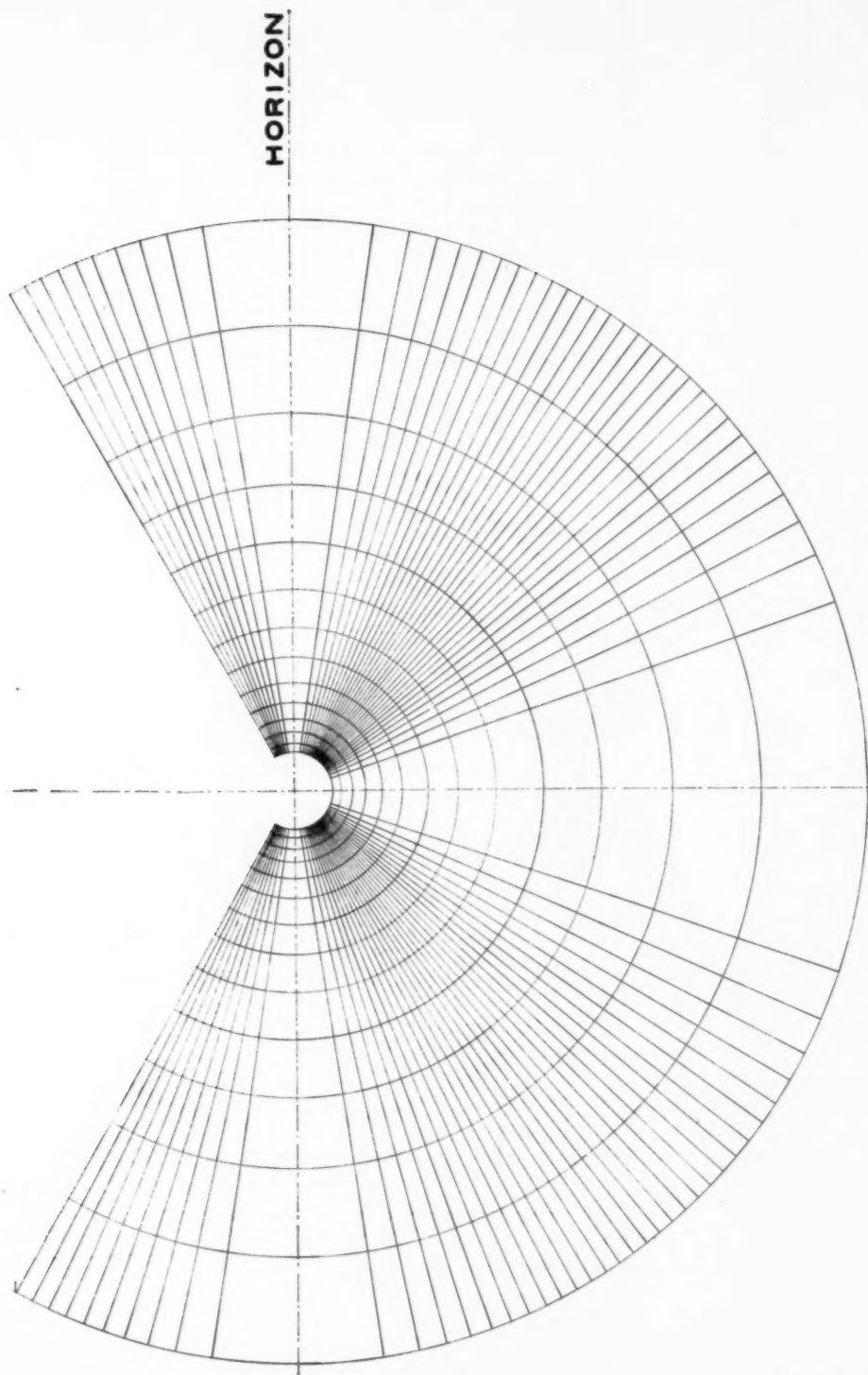


FIG. 8.—Gradient graticule *G III*. Density, 1. Unit effect, $1:10^{10}$ C. G. S.

r_{n+1} and by two radial lines embracing the angle $\varphi_{p+1} - \varphi_p$. For one element we have, therefore, to integrate the formulæ (6) within these limits or

$$\left. \begin{aligned} U_{zz} &= 3k\sigma (\sin \alpha_{m+1} - \sin \alpha_m) \int_{\varphi_p}^{\varphi_{p+1}} \int_{r_n}^{r_{n+1}} \frac{\sin^2 \varphi \cos \varphi \, d\varphi \, dr}{r} \\ U_{\Delta} &= -\frac{3}{2}k\sigma (\sin 2\alpha_{m+1} - \sin 2\alpha_m) \int_{\varphi_p}^{\varphi_{p+1}} \int_{r_n}^{r_{n+1}} \frac{\sin^3 \varphi \, d\varphi \, dr}{r} \end{aligned} \right\} \quad (7)$$

which equals

$$\left. \begin{aligned} U_{zz} &= k\sigma (\sin \alpha_{m+1} - \sin \alpha_m) (\sin^3 \varphi_{p+1} - \sin^3 \varphi_p) \int_{r_n}^{r_{n+1}} \frac{dr}{r} \\ U_{\Delta} &= -\frac{I}{2}k\sigma (\sin 2\alpha_{m+1} - \sin 2\alpha_m) \left[(\cos^3 \varphi_{p+1} - 3 \cos \varphi_{p+1}) \right. \\ &\quad \left. - (\cos^3 \varphi_p - 3 \cos \varphi_p) \right] \int_{r_n}^{r_{n+1}} \frac{dr}{r} \end{aligned} \right\} \quad (8)$$

and

$$\left. \begin{aligned} U_{zz} &= k\sigma (\sin \alpha_{m+1} - \sin \alpha_m) (\sin^3 \varphi_{p+1} - \sin^3 \varphi_p) \cdot \log_e \frac{r_{n+1}}{r_n} \\ U_{\Delta} &= -\frac{I}{2}k\sigma (\sin 2\alpha_{m+1} - \sin 2\alpha_m) (\cos^3 \varphi_{p+1} - \cos^3 \varphi_p \\ &\quad - 3 \cos \varphi_{p+1} + 3 \cos \varphi_p) \cdot \log_e \frac{r_{n+1}}{r_n} \end{aligned} \right\} \quad (9)$$

The computation of the mass elements in the graticules is based on these formulæ (9) and carried out in the following simple manner. For all graticules we draw a number of radial lines. The angles which these lines include, however, are not equal, but we assume a spacing of the lines which is in proportion to the effect of the mass elements which are formed later by the intersections of the concentric circles

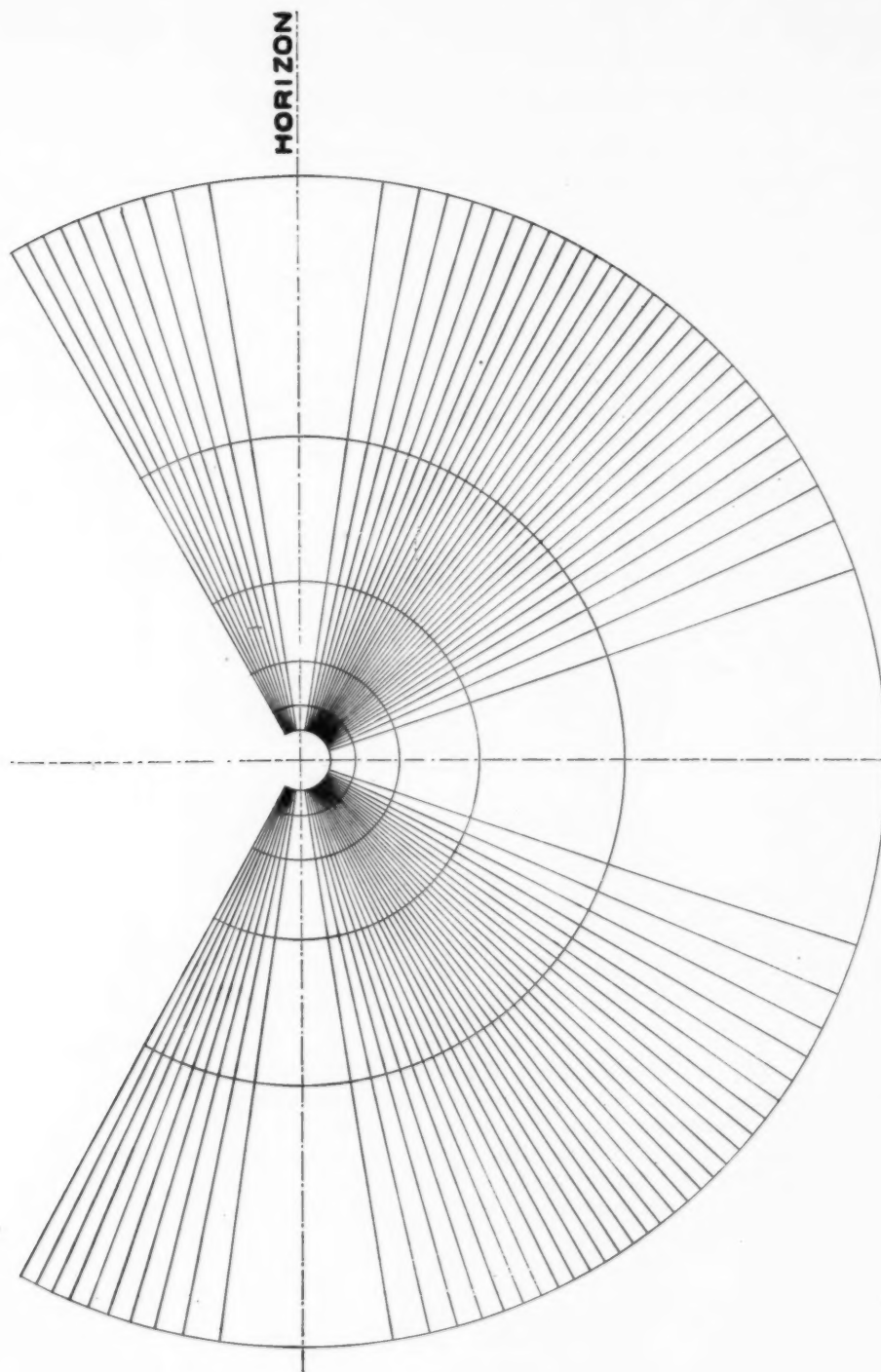


FIG. 9.—Gradient graticule *G IV*. Density, 1. 10^{10} C. G. S.

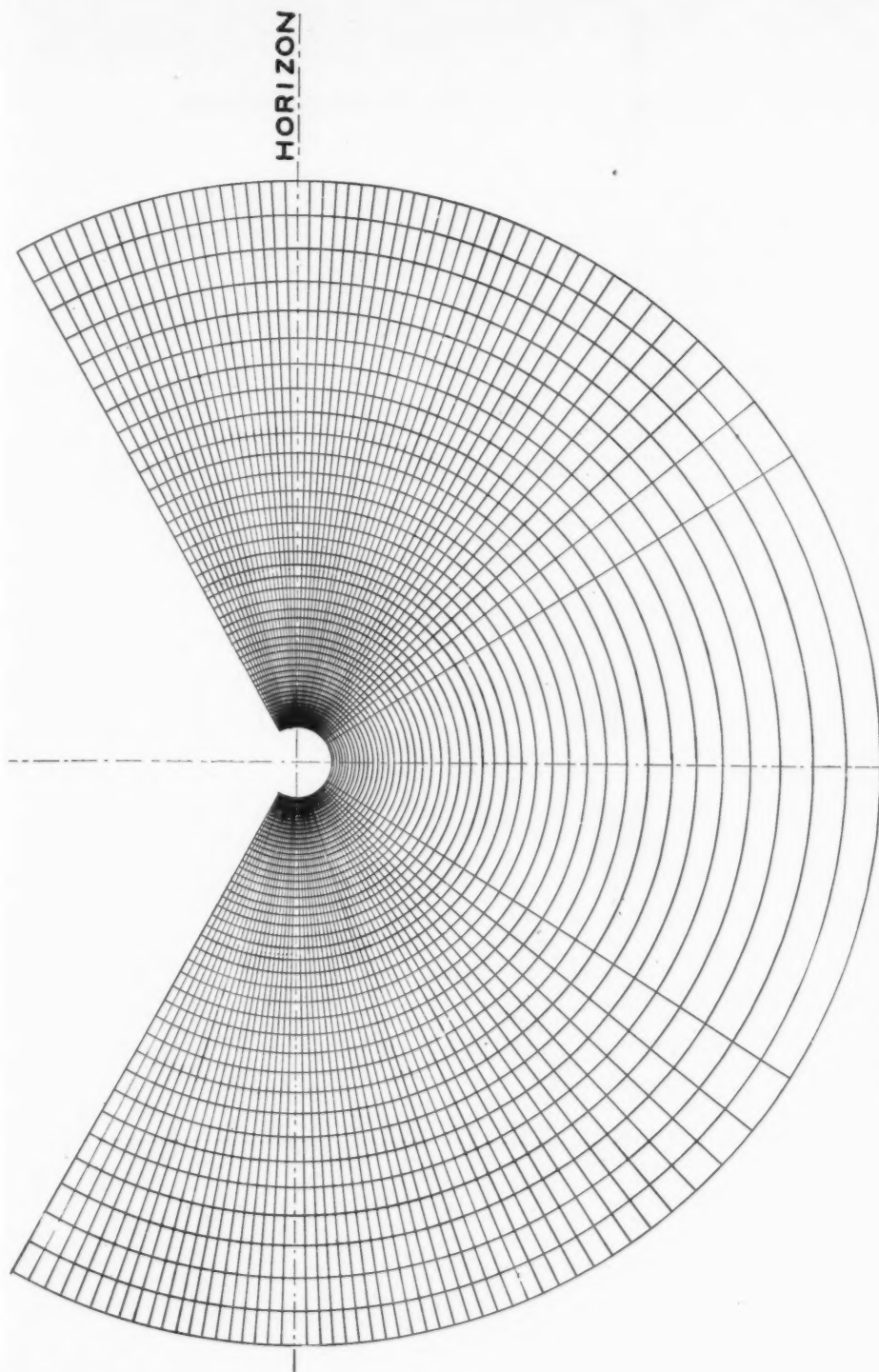


FIG. 10.—Curvature graticule *CI*. Density, 1. Unit effect, 1.10 to C. G. S.

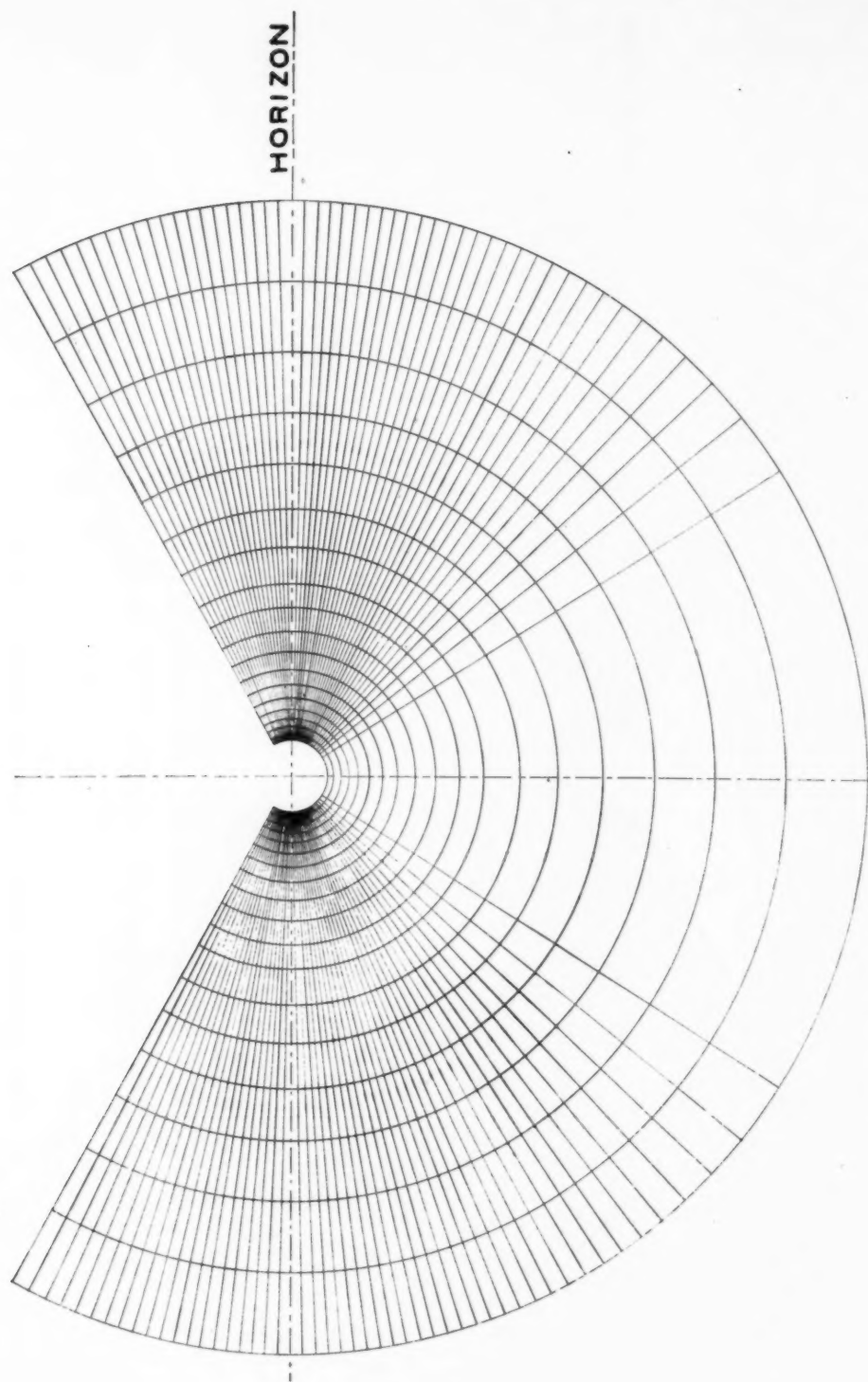


FIG. 11.—Curvature graticule *C II*. Density, 1. Unit effect, 1.10^{-10} C. G. S.

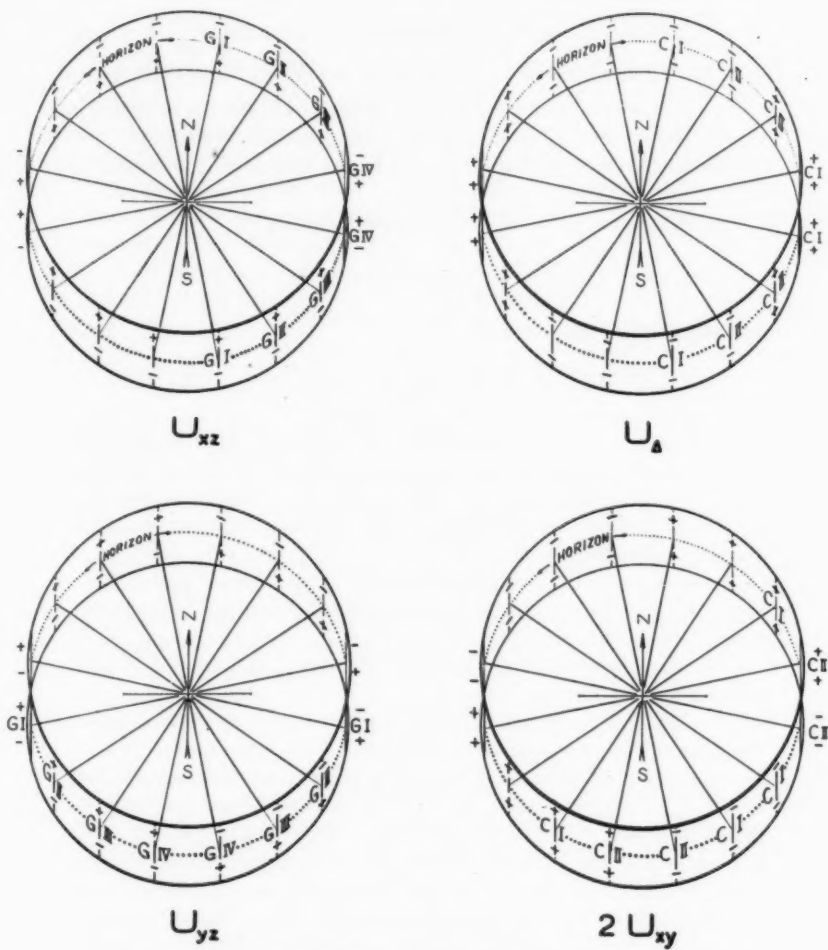


FIG. 12.—Diagrams illustrating application of gratitudes in all azimuths and above and below the horizon (through center of gravity of instrument).

$r_n, r_{n+1}, r_{n+2}, \dots$ with these lines. We thus follow a procedure previously described on page 42; that is, we take

$$\sin^3 \varphi_{p+1} - \sin^3 \varphi_p = \text{constant} = P$$

$$\cos^3 \varphi_{p+1} - \cos^3 \varphi_p - 3 \cos \varphi_{p+1} + 3 \cos \varphi_p = \text{constant} = Q$$

These constants are the same for all graticules regardless of azimuth; that is, the spacing of the radial lines is identical for all graticules.

Hence the only datum that varies as the azimuth is the spacing of the concentric circles.

Writing thus equations (9) for graticule No. I:

$$U_{xz} = k\sigma \cdot (G)_I \cdot P \cdot \log_e \frac{r_{n+1}}{r_n} \text{ and } U_{\Delta} = -\frac{I}{2} k\sigma \cdot (C)_I \cdot Q \cdot \log_e \frac{r_{n+1}}{r_n} \quad (10)$$

The equations for graticule No. II:

$$U_{xz} = k\sigma \cdot (G)_{II} \cdot P \cdot \log_e \frac{r_{n+1}}{r_n} \text{ and } U_{\Delta} = -\frac{I}{2} k\sigma \cdot (C)_{II} \cdot Q \cdot \log_e \frac{r_{n+1}}{r_n}$$

and similarly for the other graticules. After the radial lines have been drawn, properly spaced, the third dimension of the mass elements ($r_{n+1} - r_n$) may be determined. The radial extent of all mass elements is thus the same for any value of φ , which makes the construction of the diagrams extremely simple.

It is of course also possible to make the radial lines an equal distance apart, but then the radii of the mass elements would no longer be the same for any given value of φ .

The computation of the radial boundaries r_n and r_{n+1} of the elements is accomplished as follows.

For U_{xz} and U_{Δ} , a unit effect is substituted. For the application of the suggested graphical method to topographic corrections, $1 \cdot 10^{-10}$ C.G.S. is probably a good value. For the use of the graticules in interpretation, $1 \cdot 10^{-9}$ C. G. S. seems sufficient. If desired, a different unit may be chosen for gradients and curvature values. For k , we substitute $66.6 \cdot 10^9$ C. G. S.; for σ , it is advisable to use 2 if the method is applied to topographic corrections, and 0.5 ($=\Delta\sigma$) when applying the graticules to interpretation work. The reason is as follows. The surface strata have ordinarily a specific gravity of about 2, while the difference in density of many country rocks and geologic formations under study may be 0.5 and even less. With these values the evaluation of the diagrams will give at a glance the approximate terrain correction or the gravitational effect of subterranean formations. If not an approximation, but an

exact determination of either terrain or subsurface effect is desired, the values obtained from the evaluation of the diagrams must be multiplied by $\frac{\sigma^1}{\sigma}$ or $\frac{\Delta\sigma^1}{\Delta\sigma}$ respectively. If the observer wants to use one type of diagram only for both terrain correction and interpretation, it is advised to take for σ (or $\Delta\sigma$) the value of 1 and as unit effect $1 \cdot 10^{-10}$ C. G. S. For any one graticule, the constants G and C may be determined from equation (6a) and Table I. P and Q are constant for all graticules.

The computation of the radial boundaries of the elements begins with a definite distance r_n , for the inside boundary. Then the outside boundary of the element is

$$\left. \begin{aligned} \log_e r_{n+1} &= \log_e r_n + \frac{U_{ss}}{k\sigma G_{I, II, \dots VIII} \cdot P} \text{ for gradient graticules} \\ \text{and } \log_e r_{n+1} &= \log_e r_n + \frac{-2U_{\Delta}}{k\sigma C_{I, II, \dots VIII} \cdot Q} \text{ for curvature graticules} \end{aligned} \right\} (11)$$

After r_{n+1} has been computed, it serves as r_n for the computation of the subsequent r_{n+2} , and so on.

In concluding, the writer wishes to acknowledge the helpful coöperation of Jaroslav A. Malkovsky, who recently had to use the torsion balance in extremely rugged topography where it became almost imperative to apply and develop graphical methods. He will probably soon be in a position to publish details about this work and will then discuss the application of the graphic principle described to several practical problems and possible further improvements of the method. Credit is also due to W. I. Ingham, who assisted in the computation and the drafting of the diagrams.

APPENDIX

Figures 6-11 show the six diagrams which make possible the computation of the influence of any kind of topography or subterranean structure on gradients and curvature values provided eight cross sections in sixteen azimuths have been made through the terrain or the subterranean feature. These graticules are primarily intended for the computation of terrain corrections for rough and steep topography; hence, the diagrams are carried to about 30° terrain angle above the horizon (horizontal plane through center of gravity of instrument). Of course, the diagram may be readily extended to greater terrain angles by plotting more angles (which may be taken from the lower part of the diagram). The advantage of these diagrams over others published thus far is that there are no offsets in the boundaries of the elements, which facilitates the calculation of greater masses by multiplying the number of angular with the number of radial intervals which comprise the bulk of their mass. The density assumed is 1; the unit effect is $1 \cdot 10^{-10}$ C. G. S.

Each diagram consists of four quadrants, and each of these may have a different sign in respect to its effect on the quantities measured. Only the gradient diagrams (*GI-GIV*) show a difference in sign above and below the horizon; the sign for the curvature diagrams (*CI-CII*) is always the same regardless of the position of the mass elements with reference to the center of gravity of the torsion balance. The same holds for the effect of the masses on one side of the station as compared with those on the other; the signs for the gradients are always different on the two sides, but they are the same for the curvature values. As to the variation of the sign with azimuth, the sign of the gradient diagrams changes only every 180° , whereas the sign of the curvature diagrams changes every 90° . These relations are illustrated in Figure 12. This figure shows which diagram must be taken for each cross section.

A few remarks may be made about the procedure followed in the construction of the diagrams.

The fundamental equations used are given on page 63.

For the six diagrams, we compute first the constants (G)_{I...IV} and (C)_{I, II} as given by equation 6a. For σ , we substitute I ; for U_{xz} and U_{Δ} : $I \cdot 10^{10}$ C. G. S.; for k : $6.66 \cdot 10^{-8}$ C. G. S. The only unknowns are then P and Q , which are computed as follows:

The equation

$$\sin^3 \varphi_{p+1} - \sin^3 \varphi_p = P$$

may be written as an arithmetic progression, which begins with the angle 0° and ends with the angle 90° , so that the first term $a = \sin^3 \varphi_0 = 0$ and the terminal $z = \sin^3 \varphi_p = I$, where $p - 1$ is the number of intervals into which we subdivide the quadrant. Thus, the progression is

$$a, a + P, a + 2P, \dots, a + (p-1) \cdot P, \text{ or}$$

$$P = \frac{z-a}{p-1}$$

Subdividing the quadrant into 30 intervals, we have to consider 31 angles, so that $P = 0.0333 \dots$

The next step is to draw the radial lines for all diagrams, starting with 0° , so that the difference of the cubed sines of subsequent angles equals P or

$$\varphi_{p+1} = \arcsin \sqrt[3]{pP}$$

The following angles have been computed for the gradient diagrams in this manner:

18° 46'	45° 42'	62° 37'
23° 55'	47° 28'	64° 24'
27° 39'	49° 11'	66° 14'
30° 43'	50° 52'	68° 10'
33° 23'	52° 32'	70° 14'
35° 47'	54° 11'	72° 27'
38° 00'	55° 51'	74° 54'
40° 04'	57° 30'	77° 46'
42° 01'	59° 11'	81° 24'
43° 54'	60° 53'	90° 00'

The same procedure is now applied to the computation of the spacing of the radial lines in the curvature diagrams. We write the equation

$$\cos^3 \varphi_{p+1} - \cos^3 \varphi_p - 3 \cos \varphi_{p+1} + 3 \cos \varphi_p = Q$$

in form of an arithmetic progression with

$$a = \cos^3 \varphi_0 - 3 \cos \varphi_0 = -2 \text{ for } \varphi_0 = 0^\circ \text{ and}$$

$$z = \cos^3 \varphi_v - 3 \cos \varphi_v = 0 \text{ for } \varphi_v = 90^\circ$$

so that again

$$Q = \frac{z-a}{v-1}.$$

Subdividing the quadrant into 30 intervals,

$$Q = 0.0666\ldots, \text{ so that}$$

$$Q = 2P$$

The spacing of the radial lines in the curvature diagrams is thus given by the following equation for subsequent angles with subscripts p and $p+1$:

$$\cos^3 \varphi_{p+1} - 3 \cos \varphi_{p+1} = a + pQ$$

If we let $\cos \varphi_{p+1} = b$, this equation has the form

$$b^3 + 3bu + 2v = 0$$

where u and v are factors; $u = -1$ and $v = 1 - \frac{pQ}{2}$

as $a = -2$

Inasmuch as $v^2 + u^3$ is negative, only the trigonometric solution of this equation is possible by means of Moivre's theorem; the three roots are

$$b_1 = 2\sqrt{-u} \cos \frac{\Theta}{3}$$

$$b_2 = 2\sqrt{-u} \cos \left(\frac{\Theta}{3} + 120^\circ \right)$$

$$b_3 = 2\sqrt{-u} \cos \left(\frac{\Theta}{3} + 240^\circ \right), \text{ where } \cos \Theta = \frac{-v}{\sqrt{-u^3}}$$

Substituting the values here given, we find that $2 \cos \Theta = pQ - 2$ or $\cos \Theta = pP - 1$ and

$$\varphi_{p+1} = \arccos \left\{ 2 \cos \left(\frac{\Theta}{3} + 240^\circ \right) \right\}$$

The following angles have been computed for the curvature diagrams in the manner previously described:

32° 08'	63° 03'	78° 18'
38° 39'	64° 49'	79° 39'
43° 11'	66° 30'	80° 58'
46° 48'	68° 06'	82° 17'
49° 50'	69° 41'	83° 35'
52° 31'	71° 13'	84° 54'
54° 58'	72° 40'	86° 10'
57° 12'	74° 07'	87° 28'
59° 14'	75° 33'	88° 44'
61° 13'	76° 57'	90° 00'

After the spacing of the radial lines has been made for both types of diagrams, the computation of the radii is readily accomplished. For

$$Q = zP, \text{ therefore, } \frac{U_{xz}}{P} = z \frac{U_{\Delta}}{Q}; \text{ after}$$

substituting

$$S = \frac{M \cdot U_{xz}}{k\sigma P}, \text{ where } M \text{ is the modulus of Brigg's system of loga-}$$

rithms, we have

$$\log r_{n+1} = \log r_n + S \cdot \frac{I}{(G)_{I, \dots, IV}} \text{ for gradients and}$$

$$\log r_{n+1} = \log r_n + S \cdot \frac{I}{(C)_{I, II}} \text{ for curvatures.}$$

Writing for $S \cdot \frac{I}{(G)_{I, \dots, IV}} : (F)_{I, \dots, IV}$ and for

$$S \cdot \frac{I}{(C)_{I, II}} : (E)_{I, II},$$

we may compute the radii from the following arithmetic progressions of their logarithms:

$$A, A + (F)_{I, \dots, IV}, A + 2(F)_{I, \dots, IV}, \dots, A + (n-1)(F)_{I, \dots, IV}$$

for gradients and

$$A, A + (E)_{I, II}, A + 2(E)_{I, II}, \dots, A + (n-1)(E)_{I, II}$$

for curvatures, where A stands for the logarithm of the first distance. As 90 cm. is the smallest distance of most torsion balances from the ground, $\log 90$ was substituted for A , but any other distance would do just as well, because the scale of the diagrams is arbitrary.

The following tabulation gives the results of the computation of these radii, not all of which, however, are shown in the diagrams on account of scale:

TORSION BALANCE—TOPOGRAPHIC CORRECTIONS 67

<i>G I</i>	<i>G II</i>	<i>G III</i>	<i>G IV</i>
90	90	90	90
101	103	111	103
114	119	136	294
128	137	168	531
144	157	207	960
162	180	254	1735
182	207	313	3135
205	238	385	5665
231	273	475	10238
260	314	584	18500
292	361	719	33437
329	415	885	
370	476	1089	
416	547	1341	
468	629	1651	
526	722	2032	
592	830	2501	
666	954	3079	
746	1096	3790	
842	1259	4666	
948	1446	5743	
1066	1662	7070	
1199	1909	8703	
1349	2194	10712	
1518	2520	13183	
1707	2896	16233	
1920	3327	19982	
2160	3822	24597	
2430	4392	30278	
2734	5046		
3075	5798		
3459	6661		
3891	7653		
4377	8793		
4924	10103		
5539	11608		
6231	13337		
7009	15323		
7885	17606		
8870	20228		
9978	23241		
11224	26703		
12627	30680		
14204			
15978			
17974			
20219			
22745			
25586			
28782			
32378			

<i>CI</i>	<i>CI</i>	<i>CII</i>
90	1393	90
95	1484	105
102	1582	122
109	1686	143
116	1797	167
124	1915	194
132	2041	226
141	2175	264
150	2318	308
160	2471	359
171	2634	419
181	2807	489
193	2991	570
206	3188	665
220	3398	775
234	3621	904
249	3860	1054
266	4113	1229
283	4384	1434
302	4672	1672
322	4980	1950
343	5307	2274
366	5656	2653
390	6028	3094
415	6425	3608
443	6848	4208
472	7298	4907
503	7778	5723
536	8280	6674
571	8834	7786
608	9416	9077
649	10035	10346
691	10695	12347
737	11399	14400
785	12149	16794
837	12948	19586
892	13799	22843
951	14707	26640
1013	15674	31070
1080	16705	
1151	17804	
1226	18975	
1307	20223	

The application of the diagrams is as follows:

a. *For terrain corrections.*—Profiles are made through the surrounding topography (either by leveling for any arbitrary distances, or from contour charts) in the azimuths shown in Figure 12 ($11\frac{1}{4}^\circ$, $33\frac{3}{4}^\circ$, $56\frac{1}{4}^\circ$, etc.). The profiles are drawn to scale (vertical equal to horizontal scale). Then the diagrams are placed on these profiles as demonstrated in Figure 12 (for U_{xz} : $G I$ on $11\frac{1}{4}^\circ$ profile, $G II$ on $33\frac{3}{4}^\circ$, etc.; for U_{yz} : $G IV$ on $11\frac{1}{4}^\circ$ profile, $G III$ on $33\frac{3}{4}^\circ$, etc.; for U_{Δ} : $C I$ on $11\frac{1}{4}^\circ$, and $C II$ on $33\frac{3}{4}^\circ$, etc.; for $2U_{xy}$: $C II$ on $11\frac{1}{4}^\circ$, and $C I$ on $33\frac{3}{4}^\circ$, etc.). The diagrams may be preferably copied on tracing cloth and be placed on the profile lines, or the profiles may be drawn on tracing cloth and may be placed on the diagrams. Then, in every azimuth, the excess of masses above the horizon is determined as well as the deficiency below the horizon by counting the number of mass elements that are embraced by the profile line and the horizon. The horizon must be placed through the center of gravity of the instrument. The excessive masses are taken positive, the deficiencies negative; their effect must be multiplied with the signs applied to masses above and below the horizon shown in Figure 12. These signs change with the azimuth of the profile which also is shown in Figure 12. For every azimuth, the mass elements are counted and provided with the proper sign of their effect; finally, their sum is formed for the eight cross sections. This sum is multiplied by the average density of the rocks surrounding the station, provided that the nature of the geologic formation permits the application of such average value. The terrain correction for any of the four derivatives is $1/10$ of the negative sum of the elements multiplied by average density, expressed in Eötvös units. Ordinarily it may be necessary to draw the terrain profiles twice with different scales. If the height of the center of gravity is approximately one meter, the diagrams are first used with profiles drawn for distances from 1 to 15 meters, then from 15 to 225 meters, if necessary. Of course, the vertical and horizontal scale of the profiles must always be equal.

b. *For mass corrections, in underground work.*—The diagrams may be used not only for the computation of mass corrections in surface work, but also when measurements are made in tunnels and crosscuts of mines. For this purpose, the diagrams are completed so that the mass elements fill the entire circle. Before the instrument is set up, eight sections of the tunnel are determined with a transit or compass and a short adjustable vertical rod with a horizontal adjustable slide attached to it. This rod is set up in the correct azimuth as determined by the compass or transit, and the deviation of the stope from a straight vertical line and the height of the tunnel is measured. The distance of the rod from the instrument is measured by a tape, and thus the shape of the tunnel section is accurately determined in any azimuth and distance. These sections are placed on the diagrams, and the excesses or deficiencies of the mass elements are counted, with reference to concentric circles about the center of gravity of the balance. This correction is of course smaller the more carefully the center of gravity of the balance was placed in the geometric center of the tunnel.

c. *For interpretation work, that is, for the computation of depth and size of the formation or structures under investigation.*—Suppose a plan of torsion-balance stations, showing gradients and curvature values, is available. There are

several stations on the plan, lying in an almost straight line where the gradients are zero.¹ Stations on either end of this line begin to show increasing gradients toward its center the farther away they are from it. Stations on either side of this line show gradients which are perpendicular to the line; they increase in magnitude a certain distance away from the line and then decrease. The curvature values are not zero where the gradients are zero, but parallel to the line to which we refer. Their magnitude is greatest where the gradients are zero but decreases on either side of the line; at a certain distance away from the line the curvature-value lines even turn around so as then to be perpendicular to the main line.

The principal characteristics of gradients and curvature values become very clear if, in addition to a plan view, they are represented by curves. A line is drawn through the structure preferably at right angles to the strike (which may always be readily recognized from the torsion-balance results). This line is the abscissa in the diagram to be made; on this abscissa we plot the stations, properly spaced, through which the profile line goes. It is possible to shift into this line many stations that are not too far away from the profile line parallel with the direction of strike. After having plotted the stations as abscissas, gradients and curvature values are plotted as ordinates as follows. From the plan the total value of the gradient G (or the length of the arrow), and the angle β between its direction and the direction of the profile, may be obtained; also the length R of the curvature lines and the angle γ between their directions and the direction of the profile. Then the following quantities are plotted as ordinates: $G \cos \beta$ for gradients and $-R \cos 2\gamma$ for the curvatures. It is thus clear that an arrow which is perpendicular to the profile line must be plotted as 0; the same holds for curvature lines that make an angle of 45° with the profile. If the profile line runs for example from the southwest to the northeast, arrows pointing in the northeast direction are plotted as positive ordinates and arrows pointing southwest as negative values. Curvature lines parallel with the strike of the formation will, therefore, be plotted as positive ordinates and curvature lines at right angles to the strike will be plotted as negative ordinates. Such diagrams representing the torsion-balance results in form of curves are especially useful in interpreting effects of two-dimensional structures.

Referring to the example of a survey here given, it may be assumed that a torsion-balance observer with some experience will readily notice that the described effects are produced by an anticline composed of material heavier than the overlying formations. The crest of this anticline can be readily located (provided the gradients at the same distance from the crest have the same magnitude; that is, if the gradient curve is symmetrical), as it is vertically below the line of stations which show no gradient and maximum curvature deflection. The strike of this line, together with the direction of the curvature-value lines here, is the strike of the anticline. However, this is not a complete anticline, but rather an elongate dome-like feature, as the line without gradient deflection does not go entirely through our map. In other words, the outline of this feature can be fairly well traced. This is probably all the general infor-

¹The chart referred to is similar to that on page 25 of the *Colorado School of Mines Quarterly* (Jan. 19, 1929), "Geophysical Methods; Principles and Recent Successes."

mation which the torsion-balance observer may be able to get from his gravity chart. The next step is to study very carefully the geologic condition of the vicinity. Well logs must be investigated and preferably the vertical change of the specific gravity of the formations of the log must be studied. After it has been determined which formation shows an abrupt change of its specific gravity, say a limestone bed, the thickness of this formation must be approximately determined. From the investigation of the well log the density of the adjacent formations also may be determined; consequently, the $\Delta\sigma$ to be used for the diagrams is known.

Using as much geologic information as there is available, the general information obtained from a mere inspection of the gravity chart may be further extended by using the following four types of diagrams representing the gradient and curvature curves for subterranean features with geometric outlines: (a) diagrams showing a series of gradient and curvature curves for slabs with a vertical face, their extent being infinite on the other side and in the direction of strike, for various depths of the top of the slab which are multiples of its thickness; (b) diagrams of the same type as (a) except that the face is inclined; the curves, therefore, must not only be computed for various depths of the top of the slab but also for various inclinations of the face; (c) diagrams of a type similar to (a) and (b), but for formations with two vertical or two inclined faces, and infinite in the strike. The cross section of such formations would be rectangles (for vertical dikes), rhomboids (for inclined dikes on dipping beds), trapezoids (for salt domes and igneous intrusions) and triangles (anticlines), etc.; (d) diagrams and tables showing the variation in amplitude of gradients and curvature values for various ratios of width across, to width in the direction of strike of the formations covered by diagrams a, b, c (in other words for cases where their extent in strike may not be considered infinite). This ratio may be determined from the survey. Whether or not diagrams a and b are applicable may also be determined directly from the result of the survey, as gradients show positive amplitudes only for formations infinite at one end. This not being the situation, diagrams c must be applied.

Any company doing extensive torsion-balance work should keep a number of such diagrams on file, the more the better. These diagrams may also be applied if there is more than one disturbing formation affecting the torsion balance.

However, if the gravitational anomaly is virtually due to one formation only, it may be possible to determine its depth and shape directly from the results of the survey, especially if the formations have fairly regular geometric outlines. A few examples may be sufficient. If the gradient curve shows positive values only and if it is symmetrical with reference to its extreme value, there is a horizontal subterranean formation which is infinite at one end and has a vertical face. The depth of its surface and its thickness may be computed directly from the maximum gradient and the distance between the point where this maximum occurs and the point where the gradient decreases to one-half of this extreme value. If the gradient curve is unsymmetrical, the face of the formation is inclined; the inclination, depth, and thickness may be computed from a combination of gradient and curvature-amplitude, especially extreme values and their abscissas, which, however, is a rather complicated procedure.

If the gradient curve shows positive and negative amplitudes, there occur formations underneath with a limited extent across the strike. The amplitudes of maximum and minimum gradient are equal if the subterranean feature has vertical faces (a vertical dike for example). A dipping bed shows a difference in these two amplitudes; the dip may be computed from the ratio of the amplitudes or from the combination of gradients and curvature values, which, however, is a rather complicated procedure. The determination of width and surface depth of a vertical dike is much simpler; these data may be obtained from the maximum value of the curvature and the horizontal distance between the points where this maximum occurs and another point where the curvature decreases to one-half of this maximum value.

Returning to our example, the observer will have obtained an idea about the approximate depth and the slope of the flanks after applying the diagrams previously described. However, geologic formations ordinarily exhibit irregular outlines; moreover, the diagrams hold for infinite structures and the corrections for limited extent in strike are approximate only. The observer, therefore, assumes a structure which does not have straight geometrical outlines, but curved outlines, and has in general exactly the dome-like shape which is to be expected from geologic data. Exact determination of depth and dimensions of subterranean formations are possible only by applying diagrams which allow the determination of the effect of irregular outlines. The observer applies the diagrams herein described as follows. Through every station he draws sections in eight directions which cut out a definite part of the structure. After placing these sections, which may have been drawn on tracing cloth, upon the diagram which must be used for the respective azimuth, he counts the elements comprised by the outline of the structure (limestone bed) in every section, provides the sum in every azimuth with the correct sign, forms the sum total of these sums, and multiplies it by $0.1 \cdot \Delta\sigma$. This is done for all four derivatives, and for every station of the survey. These results are plotted as if they were the result of a field survey, and compared with the data which have actually been obtained in the field. If there is a discrepancy, the subsurface assumptions are changed and the theoretical results are computed again in the manner previously described. If the second trial fails to reduce the difference of observed and computed results, the assumed structure must be modified a third time, and so on. This procedure may seem very tedious and slow, but it furnishes an accuracy in the determination of the depth and the shape of the disturbing formation which is remarkable and unequalled by any other geophysical method. In his consulting practice, the writer has frequently made depth determinations of torsion-balance results which were checked by later drilling within 1 per cent. Of course it can be readily seen from these descriptions that no definite rule can be given for making interpretations of torsion-balance results. The success of the interpretation depends always to a very great extent upon the completeness of the available geologic data and also upon the character of the results (amplitude of the anomalies and pronounced alterations as distance).

The procedure previously mentioned is only a very general example of an interpretation. The interpretation may be much easier or much more difficult under other conditions, especially if there are more than one disturbing formation or an irregular distribution of specific gravities.

It is the custom with some operators to construct isogams (lines of equal relative gravity); some companies base their interpretations only upon the shape and distance of these lines. It must be emphasized, however, that isogams are totally inadequate means of interpretation. The anomaly in relative gravity produced by formations of a definite thickness depends only upon this thickness and is independent of the depth of this formation. Secondly, the relative gravity curve is almost identical for a formation with a slightly inclined face and a block with a vertical face. The isogams should be used only to obtain a very crude idea about the outline of the disturbing formations.

The diagrams shown in Figures 6-11 may also be used for structures or formations which are virtually infinite in the direction of strike. The application of these diagrams is then exactly the same as if the structure were finite; the observer will readily discover for himself when he may stop counting the elements, that is, when they become so large that their influence is negligible. However, it will be more expeditious to use diagrams such as illustrated in Figure 1, which are especially constructed for such infinite structures.

The illustrated diagrams may, finally, also be applied to the interpretation of magnetic anomalies. However, the importance and reliability of such diagrams for magnetic interpretations is much more limited than their application to the interpretation of gravitational anomalies. This is due to the fact that a homogeneous magnetization of the subterranean formations may never be assumed as correctly as a homogeneous density. (1) The theory of the magnetic potential shows that a body of any shape has a homogeneous magnetization only if it is bounded by planes of second order (in other words, formations having the shape of spheres or ellipsoids of rotation, which hardly ever occur in nature); (2) the distribution of magnetite (which virtually is the only important mineral causing magnetic anomalies) changes much more from place to place in a formation than the specific gravity and depends very much, especially in igneous rocks, on the mechanical and thermal history of the formation; (3) the direction of the magnetization may be contrary to that which may be normally expected, a condition not met with in gravity work. If our diagrams, therefore, are applied in magnetic interpretation, it must be borne in mind that the results can be approximations only.

According to the theorem of Poisson, the magnetic potential of a homogeneously magnetized body equals the gravity component parallel with the direction of magnetization multiplied by the intensity of magnetization.

From this it follows that there is a direct relation between the quantities measured by the torsion balance and the intensity of the earth's magnetic components for any one particular body, which produces a noticeable gravity anomaly as well as a magnetic disturbance. Formulæ for these relations have been published by R. v. Eötvös,¹ L. Steiner,² and H. Haalck.³

¹R. v. Eötvös, "Bestimmung der Gradienten der Schwerkraft und ihrer Niveauflächen mit Hilfe der Drehwaage," *XV. Allgemeine Konferenz der Internationalen Erdmessung* (Budapest, 1906).

²L. Steiner, "R. de Eötvös' Law Concerning the Connection Between the Local Disturbances of the Magnetic Force and Those of Gravity," *Terr. Magn. and Atm. Electr.*, Vol. 26 (1921), pp. 81-90.

³H. Haalck, "Zur Frage nach der Ursache von lokalen gravimetrischen und erdmagnetischen Störungen und ihre wechselseitigen Beziehungen," *Zeitschrift für Geophysik*, Heft 6 (1928), Seite 263-72.

From these formulae it may be seen that it is possible to determine the magnetic susceptibility of a magnetic formation from combined torsion-balance and magnetometer measurements, provided that the two types of anomalies are produced by one formation only.

It follows further from these relations that we can derive from the gravity effects which we may have computed for any type of subterranean formation, also the magnetic anomalies produced by this formation; the transformation consists essentially of a division of the somewhat modified gravity effects by the difference in density and a multiplication by the difference in susceptibility.

Therefore, we may use our gravity diagrams for magnetic interpretations by transforming the computed gravity values into magnetic anomalies as follows.

Suppose the magnetic vertical anomaly ΔZ and the horizontal anomaly ΔH have both been determined in the area under investigation. Then we plot for each station of the survey a quantity " D " which is $2\Delta H + \Delta Z \cot I$, where I is the average inclination in the area under survey, to be taken from a government map. Then we apply an error and trial method as described before; we assume a certain type of magnetic structure and determine the value of " D " for all our stations. If theoretical and observed values do not check, the subterranean structure is changed until the difference of both values is small enough.

For the computation of " D " we use the diagrams as illustrated in Figures 6-11; however, we orient them with reference to magnetic north and not astronomical north. We then compute U_{xx} and U_{Δ} for each station in the manner described before and obtain " D " by applying the formula

$$D = \frac{H}{k} \cdot \Delta q (c U_{xx} - U_{\Delta})$$

where H is the average horizontal intensity in the area under investigation, Δq the difference in magnetic susceptibility of adjacent formations and the structure or formation considered, k the gravitational constant (which in this formula should, strictly speaking, be multiplied by $\Delta \sigma$ which, however, is equal to 1 in our diagrams) and

$$c = \cot I + 2 \tan I.$$

Summing up the applications of the new graphical method as described, it appears that it may rightly be termed a universal method, as it may be employed for terrain corrections, for mass corrections in underground work, and for the interpretation of the effect of two- and three-dimensional structures, not only upon the derivatives of gravity, but also upon the magnetic horizontal and vertical intensity.

IS GEOLOGIC DISTILLATION OF PETROLEUM POSSIBLE?¹

WILLIAM L. RUSSELL²
New Haven, Connecticut

ABSTRACT

The physical, chemical, and geologic evidence bearing on the geologic distillation of petroleum is considered critically. The hydrocarbons of petroleum heavier than gasoline could not have been distilled, for their vapor pressures are much less than the rock pressures at the corresponding temperatures, and the vast volumes of natural gas necessary for their distillation under partial pressures were generally not present. The chemical evidence is also against the extensive geologic distillation of oil, because of the comparative scarcity of unsaturated hydrocarbons. The geologic evidence points toward the same conclusion, because of the distribution of the gravity variations, the absence of the requisite volumes of gas, and the general lack of diluted brines.

* It has long been customary for geologists to speak of the origin of oil by distillation. Yet these same geologists, when discussing the origin and accumulation of petroleum, generally assume that it has been at all times in the liquid state. It is important that this inconsistency should be cleared up, for the mode of migration of a gas may be quite different from that of a liquid, and the problems of oil accumulation can not be satisfactorily solved until it is known whether the oil during its migration was a liquid or a gas.

The writer is indebted to Isaac N. Beal for valuable suggestions and data, and for a criticism of the manuscript.

PREVIOUS OPINIONS

Though many geologists refer to the "distillation of oil" in their publications, there is, as far as the writer has been able to ascertain, no paper showing that distillation is possible under the physical conditions to which oil is subjected under burial. Many geologists have expressed doubt that geologic distillation has occurred, and Washburne³ long ago stated that it was impossible. The writer⁴ also made this statement in a previous paper. It seems that many geologists have used the word

¹Manuscript received by the editor, November 2, 1928.

²Geologist, Creek Drilling Company. Permanent address, 430 Temple Street.

³C. Washburne, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 3 (1919), pp. 345-62.

⁴W. L. Russell, "The Proofs of the Carbon-Ratio Theory," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), p. 979.

"distillation" in the sense of dissociation or generation, without intending to imply, necessarily, generation in a gaseous state. In a recent personal communication,¹ Rich states that the word distillation was used in this sense in his paper entitled "Generation of Oil by Geologic Distillation during Mountain Building,"² and that the main conclusions of his paper do not conflict with the views here expressed by the writer. Owing to this double usage of the word, it is in many cases impossible to tell what a writer means by a given statement. In order to prevent such confusion in the future, it is suggested that the word "distillation" be employed only to express production in a gaseous state, this being the sense in which it is used in the present paper.

PHYSICAL DATA

Obviously the best method of settling the problem under consideration is to ascertain as far as possible the physical properties of petroleum under the temperatures and pressures which exist at different depths beneath the earth's surface. The most important properties in this connection are of course the vapor pressures and the critical points.

Methods of constructing Figure 1.—Figure 1 is introduced in order to show the data graphically, and particularly to emphasize the relative order of magnitude of the vapor pressures of oil and the rock pressures. It will be noticed that an increase of 1° F. for every 30 feet of depth is assumed. The actual temperature gradients observed in oil fields range from about 1° in 30 feet or slightly less to about 1° in 100 feet. The first figure is taken, not because it is the average, but because it is most favorable for distillation. It is also assumed that the rock pressure, or hydrostatic pressure on the fluid contents of the porous strata, increases at a rate of 0.40 pounds per foot of depth, this being fairly close to the average figure. The data for the vapor pressures of gasoline and kerosene, and the figures for the critical points are taken from material assembled by Cross.³

Distillation in the absence of fixed gases.—If no gases are present and the temperature is less than the critical temperature, a liquid will begin to distill only when the vapor pressure is equal to, or greater than, the hydrostatic pressure. In dealing with petroleum, the situation is complicated by the fact that the liquid consists of many hydrocarbons which differ widely in their boiling points and vapor pressures. Fortunately,

¹J. L. Rich, personal communication, November 3, 1928.

²J. L. Rich, "Generation of Oil by Geologic Distillation during Mountain Building," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1139-50.

³R. Cross, *Kansas City Testing Laboratory Bull. No. 17*, p. 292.

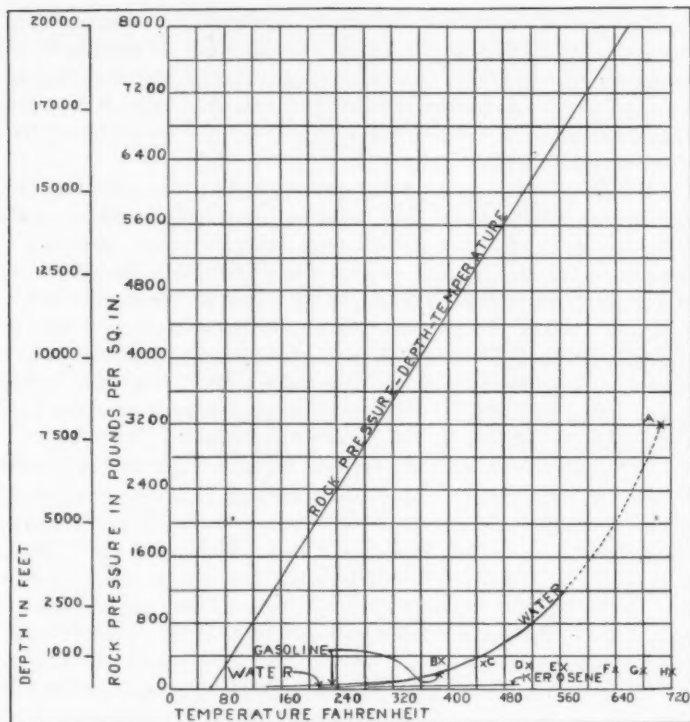


FIG. 1.—Diagram showing relation between rock pressure, depth, temperature, and the vapor pressures of water, gasoline, and kerosene. Letters indicate critical points of water and gasoline hydrocarbons. See Table I for legend.

however, the problem may be simplified for the present purposes by treating the different fractions of oil as units. As shown in Figure 1, the vapor pressure of gasoline is much higher than that of kerosene, just as the vapor pressure of kerosene is much higher than that of the heavy fraction of oil. Hence, if it can be shown that gasoline and kerosene could not distill under the temperatures and pressures to which they are subjected after burial, it would obviously be impossible for the heavier fractions with still lower boiling points to distill. It is evident from Figure 1 that the combined vapor pressures of gasoline and kerosene do not even remotely approach the rock pressure for the corresponding temperatures and depths. Hence, the distillation of petroleum at temperatures below the critical temperatures of its constituents would be

impossible in the absence of fixed gases. It should also be noticed that, while the vapor pressure of water is lower than that of gasoline at low temperatures, it is higher at high temperatures, and is greater than the vapor of kerosene and heavy oil at all temperatures. Hence, it is obvious that water would be distilled from the rocks before even the lighter fractions of the crude oil.

Limiting temperatures.—Before proceeding further in the discussion, it is necessary to consider what limits may reasonably be placed on the temperatures to which the petroliferous rocks have been subjected. Perhaps the coals and bituminous shales associated with the oil-bearing strata afford the best method for placing a limit on the maximum temperatures. When heated, these coals and bituminous shales begin to dissociate or change their nature at temperatures ranging from 600° to 800° F. Since these changes have not taken place in the coals and bituminous shales associated with the oil-bearing series, it is evident that the maximum temperature was never greater than 800° F.

Distillation under partial pressures.—If gases were associated with the oil, small quantities of vapors of the liquid hydrocarbons could exist in them. Under such conditions the volumes of the vapors would be proportional to their partial pressures. Hence, their relative proportions in the gas may be estimated from the vapor pressures shown in Figure 1. In order to illustrate the rôle which distillation under partial pressures could play in the geologic distillation of petroleum, two possible conditions will be considered, one at 400° F., the other at 600° F. At 400° F. the vapor pressure of the heavy fraction of the crude oil would be considerably less than 15 pounds per square inch, for at atmospheric pressures the part of the crude oil denser than 35° Bé. generally does not begin to distill until a temperature of about 600° F. has been reached. It will be assumed, therefore, that the absolute vapor pressure of these heavy constituents will be 5 pounds per square inch. The rock pressure corresponding to 400° F. in Figure 1 is 4,550 pounds per square inch. Under these assumptions at 400° F. the vapor pressures and relative proportions in the gas of the substances under consideration would be about as follows:

Substance	Vapor Pressure Pounds per Square Inch	Proportion in Gas
Gasoline.....	210	1/24
Kerosene.....	45	1/112
Heavy Oil.....	5	1/1,009
Water.....	235	1/21

At temperatures of 600° F. the vapor pressures and proportions in the gas would be about as follows, under the same assumptions:

<i>Substance</i>	<i>Vapor Pressure Pounds per Square Inch</i>	<i>Proportion in Gas</i>
Kerosene.....	100	1/100
Heavy Oil.....	15	1/593
Water.....	1,550	1/5.7

The rock pressure corresponding to 600° F. in Figure 1 is 7,230 pounds per square inch. The proportion of gasoline vapor is not figured, as 600° F. is above the critical temperature of most of its constituents. Under high pressures, vapors of gasoline and probably also of kerosene have the property of being absorbed in the heavy fractions of petroleum in large quantities. Hence, the proportions of gasoline and probably of kerosene would actually be much less than the figures just given. It should also be borne in mind that the temperature gradient shown in Figure 1 is exceptionally high. Another important point is that the vapors of the petroleum fractions would occupy a much smaller volume when condensed to liquids, whereas the fixed gases would expand as the rock pressure was decreased by the removal of the overburden.

It is clear, therefore, that the volume of gas required for the distillation of a given volume of oil under partial pressures would be at least 1,000 times the volume of the liquid kerosene, and at least 10,000 times the volume of the liquid heavy oil. This means that if an oil pool in a given sand covered a square mile, gas necessary for its distillation would cover at least several thousand square miles, assuming that the porosity and sand thickness remained the same.

The effect of the critical points.—Since the critical temperature is the highest temperature at which a pure substance can exist in the liquid state, and since the critical pressure is the vapor pressure of a liquid at its critical temperature, the critical points are obviously important in the present connection. The critical points of water and some of the lighter petroleum hydrocarbons are shown in Table I.¹ It is evident that the critical temperatures increase and the critical pressures decrease with the increasing density of the hydrocarbons. If a pure liquid isolated from gases and at pressures greater than its critical pressure were heated, it would nominally become a gas at the critical temperature, but there would be no abrupt change of volume or pressure. If, on the other hand,

¹R. Cross, *op. cit.*, pp. 221, 292.

TABLE I
THE CRITICAL POINTS OF WATER AND SOME PARAFFIN HYDROCARBONS

<i>Hydro-Carbon</i>	<i>Degrees Bé. Gravity</i>	<i>Critical Temperature Degrees F.</i>	<i>Critical Pressure in Atmospheres</i>	<i>Symbol in Figure 1</i>
<i>Gasoline Hydrocarbons</i>				
Pentane.....	92.2	390	24	<i>B</i>
Hexane.....	78.0	450	22	<i>C</i>
Heptane.....	70.0	515	20	<i>D</i>
Octane.....	65.0	565	18	<i>E</i>
Nonane.....	59.2	640	16	<i>F</i>
Decane.....	56.7	680	15	<i>G</i>
Undecane.....	54.2	720	14	<i>H</i>
<i>Kerosene Hydrocarbons</i>				
Duodecane.....	51.8	760	13	
Tridecane.....	46.8	860	10.5	
Tetradecane.....	45.0	900	9	
Water.....	10.0	705	217.5	<i>A</i>

it was heated in contact with a gas at pressures greater than the critical pressure, the percentage of vapor of the liquid in the gas would steadily increase until the critical temperature was reached, when it would mix in all proportions with the gas. Hence, if the gasoline hydrocarbons alone were in contact with gas, they would mix in all proportions with the gas when the temperature was greater than their critical temperatures. Actually, however, appreciable quantities of heavier hydrocarbons would generally be present. According to Cross,¹ the effect of these heavier hydrocarbons is to increase the critical temperatures of the lighter hydrocarbons associated with them, because the light constituents remain dissolved in the heavier liquid hydrocarbons. Hence, even when the gasoline hydrocarbons were heated above their critical temperatures they would generally not mix in all proportions with the associated gases, but would for the most part remain dissolved in the heavier liquid petroleum. However, above the critical temperatures the percentage of gasoline vapors in the associated natural gas would doubtless rise rapidly with the temperature.

The possibility of polymerization—Another hypothesis which must be considered is the possibility that oil is formed by the polymerization of gases or of gases and the gasoline hydrocarbons. As no chemical and physical data are at present available on this subject, it can not at present be discussed further. However, it should be noticed that this

¹R. Cross, *op. cit.*, p. 292.

could not be called distillation of oil, for the gases would not have been oil vapors, but fixed gases of different composition.

CHEMICAL EVIDENCE

If oil were distilled and condensed again without altering its composition, it would of course be impossible to detect such distillation by chemical means, since there would be no change in its chemical characteristics. However, since it is impossible to distill the heavier constituents of many crude oils without dissociation even at atmospheric pressures, a considerable fraction of the oils would evidently be dissociated if they were distilled under the great pressures existing in the buried strata. According to Cunningham-Craig,¹ equal parts of saturated and unsaturated hydrocarbons are formed by the cracking of saturated hydrocarbons. The absence or relative scarcity of such unsaturated hydrocarbons in many crude oils is therefore evidence that they have not been distilled, provided, of course, that the unsaturated molecules do not become saturated again by polymerization after distillation. Where igneous intrusions cut a bituminous or petroliferous formation, the containing rocks are raised to such high temperatures that any heavy oil or bituminous material remaining in it would be cracked. According to Cunningham-Craig,² analyses of many oils found adjacent to igneous intrusions show large percentages of unsaturated hydrocarbons. Although this seems to indicate that the oils or parent substances have been cracked, it does not necessarily mean that they have been distilled. Whether the products of dissociation were gases or liquids at the time of their dissociation would depend on the relation of the vapor pressures to the temperature. The temperatures may well have been above the critical temperatures of the gasoline and kerosene fractions, but since the heavy constituents of oil will crack before their vapor pressures become high, it is probable that these were generated as liquids.

GEOLOGIC EVIDENCE

It has already been shown that in discussing the question of geologic distillation of petroleum two possibilities must be considered, namely, the distillation of the hydrocarbons in their present proportions, and distillation under partial pressures in the presence of fixed gases. As previously stated, the physical evidence indicates that oil could not have been distilled when associated with gas in about the same propor-

¹E. H. Cunningham-Craig, *Oil Finding*.

²*Op. cit.*

tions as it now occurs, but it remains to be seen whether the geologic evidence supports this conclusion.

Figure 1 indicates that if oil with the ordinary amount of gas were subjected to heat and pressure in the presence of water, the water would become a gas before the oil, as the temperature rose, and the oil would be condensed to a liquid before the water as the temperature fell. This is because the vapor pressure of water is greater than that of petroleum at the corresponding temperatures, and because the critical temperature of water is lower than the critical temperatures of the paraffine series of hydrocarbons heavier than gasoline. Since this is true, it seems probable that if any extensive migration of distilled oil had taken place in the gaseous state it would produce recognizable changes in the distribution of the oil, gas, and water. In the gaseous state, these fluids would mix in all proportions, but as they migrated to areas of lower temperature and pressure, the heavy hydrocarbons with the lowest vapor pressure would be the first to be condensed to a liquid. Still farther away from the source the medium kerosene fractions would condense, and the gasoline fraction would be liquefied at the greatest distance from the source. The water would not condense until after the kerosene and heavy oil. It would seem, therefore, that if any extensive migration of the distilled oils in the gaseous state has taken place, the heaviest oils should be found in the areas which lay at the greatest depths or which were exposed to the greatest temperatures and pressures. The actual distribution is, however, the exact opposite. It is well known that there is a general tendency for the specific gravity of oil to decrease with depth, and the decrease of specific gravity toward areas of greater regional alteration, where the temperatures and pressures would be presumably greater, is one of the corollaries of the carbon-ratio theory.

Even if the oils were distilled under partial pressures and existed as vapors in vastly greater volumes of gas, the same zonal distribution of oil with respect to its density should be found, for the heavier fractions would invariably be the first to condense, because of their lower vapor pressure. The absence of such a distribution is therefore a proof that the extensive migration of distilled oil in the form of vapors in vast volumes of gas did not take place.

Moreover, as has been previously shown, such distillation of oil in the form of a vapor could only take place in the presence of volumes of gas several thousand times as large as the volume of the liquid oil, even if it be assumed that no oil escaped along with the gas. Not only are such vast volumes of gas not found at present associated with the oil, but

in many areas there are reasons for thinking that such great quantities of gas were never associated with it. In some places the oil sands are overlain by porous water sands interbedded with impervious shales. If a volume of gas several thousand times as great as that of the oil has escaped from the oil sands to the surface, it would seem that considerable accumulations of gas would be entrapped in the water sands where they are on anticlines and are covered by impervious shales. The absence of such extensive accumulations of gas in many places therefore suggests that such enormous volumes of gas have not made their escape.

The occurrence of brines with much larger proportions of chlorides than sea water contains might be interpreted as an argument in favor of the escape of great volumes of gas, since it has been argued that these brines become concentrated by the evaporation of water into the escaping gas. The fact that these brines are found in close association with the oil pools, however, is an argument against the idea that the oil was carried in a vapor and condensed, for under such conditions the concentrated brines should occur where the oil and water were distilled, and where they condensed there should be a diluted brine.

Another important point is that there is no real need for any theory involving the distillation of oil, for the migration and accumulation of petroleum may be explained by other processes.

CONCLUSIONS

1. Geologic distillation of petroleum in the absence of relatively enormous volumes of fixed gases is impossible except near igneous intrusions.
2. Although small quantities of the lighter constituents of crude oil may have been distilled as vapors in large volumes of natural gas, it is highly improbable that important quantities of crude oil have been distilled in this manner.
3. There is no necessity for assuming the occurrence of geologic distillation, for other processes are capable of explaining the migration and accumulation of oil.

DISCUSSION

JOHN L. RICH:² In presenting quantitative data to show that the vaporization of petroleum is impossible under ordinary geological conditions, Russell has rendered a timely service. He has focused attention on the confusion

²Consulting geologist, Ottawa, Kansas.

which has resulted from the prevailing use of the word "distillation" loosely and with a double meaning, and has urged that henceforth the word be used only in the sense of production in a gaseous state. Such a restriction in the use of the term is certainly desirable and necessary if confusion is to be avoided.

Authors who have previously used the word "distillation" in connection with the generation of oil by geologic processes such as regional metamorphism and devolatilization, have rarely used the word in the narrow and strictly correct sense which Russell proposes. They have used it most commonly in the sense of any process whereby oil and gas are generated from their mother substances in the rocks under the influence of heat and pressure. Whether the hydrocarbons were formed as oils or as oil vapors is a distinction which most of the authors with whose works the writer is familiar have failed to make.

In the writer's paper on "Generation of Oil by Geologic Distillation During Mountain Building"¹ the word distillation was used in the broader sense. Although care was taken to emphasize the generation of oil by cracking directly from its mother substances, oil vapors were also referred to because, at the time, it was the writer's impression that part, at least, of the petroleum would be generated in the form of vapors. The arguments presented in that paper, however, in no wise depend on the generation of petroleum in the gaseous form.

In the light of the data presented by Russell, it may be that vaporization has no place in the process of the generation of oil. "Geologic distillation" of oil, in the sense of geologic vaporization of oil, under ordinary conditions may be an impossibility, as the title and negative conclusion of Russell's paper indicate, but the large-scale generation of oil under the influence of the dynamic forces and temperatures associated with mountain building and regional metamorphism is not thereby ruled out.

In spite of the data presented by Russell, the writer believes that it would be unsafe to conclude that true distillation or vaporization of petroleum on a considerable scale is impossible until more is known about the temperatures which accompanied regional metamorphism, such as that which devolatilized the rocks of the eastern Appalachian province. The temperatures given in Russell's Figure 1 are those due to depth alone. Even making allowance for the fact that he has used a temperature gradient nearly twice as steep as the probable average, it may be that in regions undergoing metamorphism, temperatures, for the various depths, far exceed those shown. The writer does not know of any data on the probable temperatures once endured by the metamorphosed areas, but it seems possible that they may have been high enough to have exceeded the critical points of the light oils which would have resulted from the cracking of the mother substances of petroleum under those temperatures, and thus to have permitted the mingling of oil vapors with the gases in all proportions.

¹John L. Rich, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 1139-49.

REVIEWS AND NEW PUBLICATIONS

"The Determination of the Position and Extent of Simple Bodies by the Use of the Gradient and Differential Curvature Values." By CARL JUNG. *Zeitschrift für Geophysik*, Jahrgang III, Heft 6 (1927), pp. 257-80. In German.

This paper reports concisely the results of a mathematical study of the theory of the interpretation of the form, position, and size of simple bodies from the form of their gradient and differential curvature profiles as the latter would be obtained, for example, by a survey with an Eötvös torsion balance. On account of the difficulty of handling the more complicated problems, the study was restricted to bodies (a) of simple cross section, that is, horizontal prisms with vertical or inclined front and back faces, horizontal plates with a vertical or inclined face, cylinders, spheres; (b) of infinite extent at right angles to the plane of the cross section (except for the sphere); (c) of homogeneous density in a medium of homogeneous density; and (d) where the difference between the density of the body and of the surrounding medium is known. By the use of the relations of the abscissæ of the points of algebraic and numerical maximum and minimum of the gradient and differential curvature, he gives formulæ or graphs for the recognition of the presence of those simple forms of bodies and for the determination of their dimensions and of their depths below the surface. He gives also an example of the rough applicability and yet the danger of the use of the formulæ in connection with bodies that are not infinite or approximately infinite at right angles to the plane of the section.

This interesting paper is a valuable contribution to the literature on the theory of the interpretation of torsion balance results. However, unfortunately, the applicability of these many pretty formulæ will be extremely limited in practice. Most geologic structures are not long enough with reference to their depth to be treated as infinite, and are not simple enough to be represented by such simple cross sections; only a few actual structures can be treated as being of homogeneous density in a medium of homogeneous density; the density situation usually can be guessed only approximately; and in general, except for structures coming almost to the surface, the abscissæ of the distance vary rapidly with a slight change in the ordinates of the value of the gradient or differential curvature near the points of numerical maximum of the gradient or the differential curvature. With the ordinary complications of the effects of lesser anomalies and greater order obscuring the situation, the abscissæ of the algebraic maxima and minima are extremely indefinite and intangible magnitudes in practice, and the probable error in the determination of the abscissæ may be several times the significant differences indicative of the different forms of the bodies and different depths. These formulæ will have a very limited applicability in a merely approximate qualitative determination, for example, as to whether a body is $\frac{1}{2}$ mile thick and $\frac{1}{2}$ mile deep or 2 miles

deep and 2 miles thick, but in general will not give accurate enough results to be of practical use. The paper is one which should be studied by students of interpretation but should be used with great caution in practice.

DONALD C. BARTON

CONSULTING GEOLOGIST AND GEOPHYSICIST
HOUSTON, TEXAS
November, 1928

Elements of Geophysics, as Applied to Exploration for Minerals, Oil, and Gas.

By MARGARET C. COBB. Translated from RICHARD AMBRONN's "Methoden der Angewandten Geophysik," *Liesegang's Wissenschaftliche Forschungberichte Naturwissenschaftliche Reihe*, Band XV. Theodor Steinkopf (Dresden and Leipzig, 1926). McGraw-Hill Book Company (New York, 1928). 372 pp., 84 illus., 1,672 references. Price, \$5.00, postpaid.

The book is not intended to serve as a textbook for the execution of geophysical surveys, but (1) to supply a complete and well-balanced review of all the geophysical methods that may be used in economic geology, so that the geologist, mining engineer, layman, or executive who has to do with them or is considering the use of them may come as completely as possible to understand their possibilities and applicabilities, and (2) to provide, for the practical geophysicists and others interested in applied geophysics, references to the thought and literature on the subject.

The book comprises an introductory chapter on the development and present position of geophysical methods in prospecting; influence of the sub-surface formations on the character of the gravitational field at the surface of the earth, including pendulum and torsion balance surveys; magnetic methods of investigation; the use of radioactive and atmospheric-electric measurements for geophysical prospecting; electrical methods of prospecting; the seismic method of prospecting; the distribution of temperature in the earth's interior; and the use of temperature methods in applied geophysics.

In each subject, the elements of the pure as well as the applied theory are given, the geophysical instruments and their method of use are described, and the results of many applied geophysical surveys are shown and practically all published descriptions of geophysical surveys are mentioned. The literature on pure and applied geophysics apparently has been thoroughly searched and a detailed review is given of the pertinent thoughts, theories, suggestions, observations, data, and, at the point of mention, a direct reference is made to the authors and to the particular papers in which they have expressed an opinion on the subject. There are 84 diagrams, sections, maps, and a bibliography of 1,672 titles, and of 277 serials in which geophysical papers have been published.

The parts of the manuscript checked against the original by the reviewer were found faithfully to follow the German text. Minor revisions and small additions of new material were made in a few places in the book by Ambronn during the translation, but in general the book is of the date of the original, March, 1926, and the extensive literature of 1926, 1927, and first half of 1928

is not mentioned or listed. The typography is good and the illustrations clear.

The only adverse criticism which the reviewer has to offer is that in places insufficient distinction is made between practically untried methods which theoretically should work and methods which have actually been proved successful. The general impression which the book gives in regard to the successful applicability of the methods in economic geology is slightly too optimistic. The book also would have been more convenient in many ways if it had been of pocket size like the German original.

If the reviewer were allowed only one book on geophysics he would have to choose this. It will be the indispensable reference book of the professional geophysicist and the textbook of the elementary and advanced students of geophysics and of geologists, executives, and others interested in applied geophysics.

DONALD C. BARTON

CONSULTING GEOLOGIST AND GEOPHYSICIST
HOUSTON, TEXAS
November 22, 1928

Der Bau der Erde. By L. KOBER. Gebrüder Borntraeger (Berlin, 1928). 499 pp., 138 illus. Price, 27.60 M.

The second edition of this interesting book has been enlarged from 324 to 499 pages and the number of illustrations has been augmented from 46 to 138. It not only describes the structural relations of the different parts of the earth's surface, but also gives important details on the stratigraphy, facies, and structure of many areas including producing and prospective oil territory. A review sufficiently detailed to do the book justice would be beyond the scope of this *Bulletin*.

EDWARD BLOESCH

CONSULTING GEOLOGIST
TULSA, OKLAHOMA
December, 1928

RECENT PUBLICATIONS

GENERAL

"Major Marine Transgressions or Regressions and Structural Features of the Gulf Coastal Plain," by Lloyd W. Stephenson. *American Journal of Science*, 5th Series, Vol. 16, No. 94 (Oct., 1928), pp. 281-98.

"Causes and Effects of Crooked Holes," by E. J. McKee. *Oil and Gas Journal* (Nov. 22, 1928), pp. 51 and 119. *Oil Weekly* (Nov. 23, 1928), pp. 60, 62, and 66.

"Magnetic Surveying in Oil Geology," by W. H. Fordham. *Los Angeles Oil Bulletin* (Dec., 1928), pp. 1261-64; 6 figs.

MONTANA

"Sweetgrass Arch Structures," by E. B. Emrick. *Great Falls (Montana) Tribune* (Nov. 18, 1928); *The Inland Oil Index* (Dec. 7, 1928), pp. 10 and 12.

OKLAHOMA

"Oil and Gas Geology of Coal and Pittsburg Counties," by W. W. Clawson, Jr. *Oklahoma Geological Survey Bulletin 40-JJ*, 16 pp., 2 pls., 2 figs.

"Lower Cretaceous of Western Oklahoma," by Fred M. Bullard. *Oklahoma Geol. Survey Bull. 47* (Oct., 1928). Norman, Oklahoma. 116 pp., 11 plates, 7 figs. Price, \$0.57.

PERU AND ECUADOR

"Recent Developments in Peru and Ecuador," by William Gretzinger. *Oil Field Engineering* (Dec. 1, 1928), pp. 22-24, 1 map.

RUSSIA

"Characteristics of Gushers of the Grosny Region," by N. T. Lindtrop. *Petroleum Industry (Russia)*, T. 15, No. 9, pp. 305-15. In Russian.

TEXAS

"Observations on the Hendricks Field of Winkler County, Texas," by Charles H. Pishney. *Mining and Metallurgy* (Oct., 1928), pp. 463-64, 1 fig.

VENEZUELA

"A Note on the Pleistocene History of Western Buchivacoa (Venezuela)," by John Parkinson. *Quarterly Journal of the Geological Society of London*, Vol. 84, Part 3, No. 335 (Oct. 31, 1928), pp. 570-72; 1 map.

TECHNICAL PERIODICALS

The following exchange periodicals have been added to the list of the *Bulletin's* exchange publications and may be examined at Association headquarters, 504 Tulsa Building.

Azerbaijan Oil Industry (Baku)

Archiv für Lagerstätten-Forschungen und

Abhandlungen der Preussischen Geologischen Landesanstalt (Berlin). Bulletins on stratigraphy, structure, oil, coal, salt domes, and Cretaceous fossils including *Foraminifera*

Geological Magazine (Cambridge, England)

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these applicants, please send it promptly to J. P. D. Hull, Business Manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each applicant.)

FOR ACTIVE MEMBERSHIP

Samuel B. Brown, Houston, Tex.
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Henri A. Goblot, Lwow (Lemberg), Poland
I. P. Voitestii, E. T. Hancock, Ray P. Walters
Claud S. Johnston, Seminole, Okla.
Oscar Hatcher, Charles R. Hoyle, H. L. Rau
Shepard W. Lowman, Tulsa, Okla.
Earl A. Trager, Ira H. Cram, Robert H. Dott
Roy W. Merritt, New York, N. Y.
F. C. Merritt, Guy L. Goodwin, Roderick Burnham
Harold F. Moses, New York, N. Y.
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W. D. Chawner, Philadelphia, Pa.
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David C. Harrell, San Angelo, Tex.
John I. Moore, Dwight H. Thornburg, Russell C. Conkling
Howell C. Jeffery, Tulsa, Okla.
R. C. Moore, A. I. Levorsen, J. Marshall Brown

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John S. Cruse, Jr., Houston, Tex.
George M. Bevier, Sidney A. Judson, Albert G. Wolf
Donald M. Davis, Houston, Tex.
George M. Bevier, Sidney A. Judson, Albert G. Wolf

Russell W. Grimes, Muskegon, Mich.

C. C. Clark, Angus McLeod, Ernest Guy Robinson

John Ervin Hupp, Casper, Wyo.

Charles M. Rath, John G. Bartram, R. Clare Coffin

Coe Stanley Mills, Fort Worth, Tex.

Ray V. Hennen, Thomas W. Leach, R. J. Metcalf

Robert R. Osborne, Pampa, Tex.

John L. Ferguson, F. W. Bartlett, L. R. Hagy

PACIFIC SECTION MEETING, LOS ANGELES, NOVEMBER 1-2

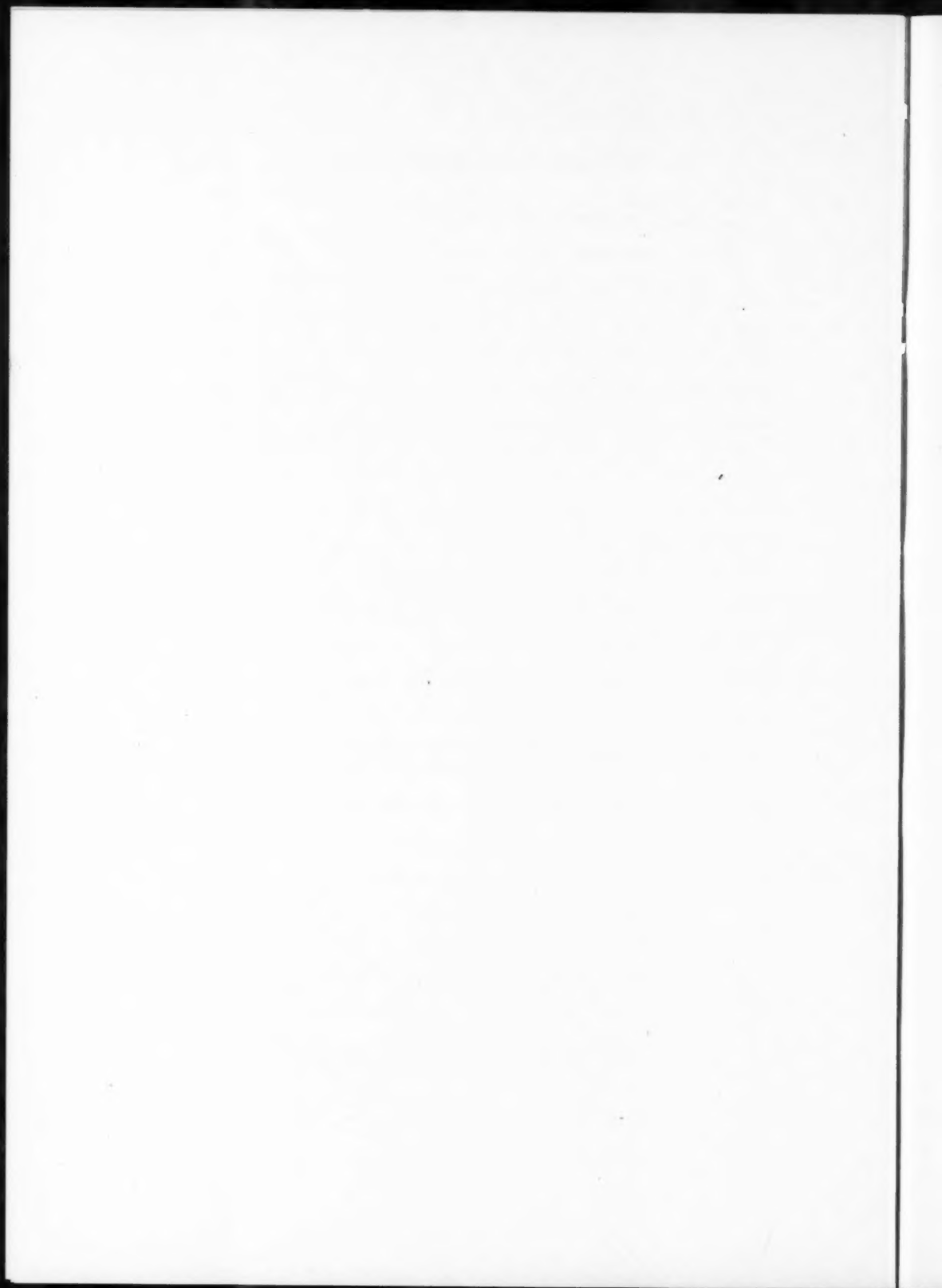
The fifth annual meeting of the Pacific Section of the Association was held at the Biltmore Hotel, Los Angeles, California, November 1 and 2, 1928. The sessions on both days were devoted largely to the reading and discussion of technical papers listed on the following program. A record-breaking attendance is reported. The outgoing officers of the section are: C. R. McCollom, chairman, and Bartlett W. Gillespie, secretary-treasurer. The officers elected for the new year are: Earl Noble, chairman, and E. M. Butterworth, secretary-treasurer. Nineteen papers were presented on the technical program.

1. Structural Problems of the Coastal Region between Ventura and Point Concepcion, California, by H. R. Johnson.
2. The Geology of the Elwood Terrace Oil Field, Santa Barbara County, California, by Frank A. Morgan, Jr.
3. The Geology and Oil Production of Elk Hills, Kern County, California, by J. R. Pemberton.
4. The Topographic Relationships of the San Andreas Fault, by Walter A. English.
5. Rotation of Crustal Blocks and Some Resulting Phenomena, by J. E. Eaton.
6. Recent *Foraminifera* from the Vicinity of Santa Catalina Island and their Relation to Fossil *Foraminifera* of the Los Angeles Basin, by Manley L. Natland.
7. The Geologic Age of the Modelo Formation, by F. H. Hudson and E. K. Craig.
8. The Geology of the Santa Monica Mountains west of Topanga Canyon, by Wayne Loel.
9. Contribution to the Late Tertiary and Quaternary Stratigraphy of the San Joaquin Valley, by P. P. Goudkoff.
10. The Torsion Balance in California, by R. H. Miller.
11. One of the Great Problems of the Pleistocene, by Frederick P. Vickery.
12. The New Kettleman Hills Oil Field, by G. W. Corby.
13. The Long Beach Oil Field, California, by S. Sweeney.
14. Storage and Repressuring in Brea-Olinda Oil Field, by F. W. Lake.
15. Corrective Methods for Drilling Straight Holes, by Martin Van Couvering.
16. The Coalunga Oil Field, by Andrew M. Hazzard.
17. The Santa Fé Springs Oil Field, California, by Donald K. Weaver.

18. Gas Conservation at Santa Fé Springs, by A. C. Rubel.
 19. The Rincon Oil Field, by L. E. Porter.
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EXECUTIVE COMMITTEE AT TULSA, NOVEMBER 28

The Executive Committee of the Association met at headquarters, 504 Tulsa Building, Tulsa, November 28, 1928. President R. S. McFarland of Tulsa, Oklahoma, first vice-president John E. Elliott of Los Angeles, California, and third vice-president John L. Rich of Ottawa, Kansas, were present. A considerable amount of routine business was enacted. President McFarland reported (1), the purchase of a large fireproof safe and new steel shelving for records and books, and (2), the satisfactory handling of Association securities through the service of a reliable and experienced investment company.



Memorial

CARL W. CLARKE

It is with the deepest sorrow that we chronicle the death of Carl W. Clarke on September 13, 1928, at Oklahoma City. To his many close friends and business associates the news of his tragic end, through an accidental fall from the window of a fifth-floor room of the Huckins Hotel, was as grievous as the passing of a loved brother. His sunny disposition, his always-ready smile and cheerful greeting, combined with an unusually kind and generous nature, had made for Carl such a wide circle of intimate friends as it is the good fortune of few men to possess. Though young in years, his judgment was that of maturity, and as a comrade and adviser he was esteemed by all.

Carl W. Clarke was born at Vinita, Oklahoma, November 8, 1896. He was one of six children born to Mr. and Mrs. J. F. Clarke, who were pioneer settlers of Oklahoma. The mother, Mrs. J. F. Clarke, and two sisters, Misses Elizabeth and Elaine, now live at Henryetta. A third sister, Mrs. M. A. Nash, is the wife of the president of the Oklahoma College for Women at Chickasha. A brother, Ralph, is in the employ of the Darby Petroleum Corporation in the St. Louis area, and another brother, Ronald, resides at Springdale, Arkansas. The elder Clarke died some years ago.

Carl graduated from the University of Oklahoma in 1918 with the degree of Bachelor of Science in Geology. During the summer months of 1915 and 1916 he was associated in consulting work with Carl D. Smith of Tulsa. In 1917 he spent several months on the island of Haiti in the employ of S. Pearson and Son.

When the United States entered the World War, Carl enlisted, January 1, 1918, in the 606th Engineers, of Fort Logan, Colorado. He went overseas with this organization, but was transferred, soon after reaching France, to Company M of the 29th Engineers. He served with the 29th in France from November, 1918, to February 1, 1919. He was transferred with this unit to the Army of Occupation at Coblenz, Germany, where he remained until August 11, 1919. He received honorable discharge at Camp Pike, Arkansas, on September 5, 1919.

Following his service in the army, Carl entered the employ of the Amerada Petroleum Corporation, doing geological work in Oklahoma and Kansas. He left the Amerada in 1921 and spent several months in consulting work at Okmulgee. In July, 1922, he became chief geologist of the Darby Petroleum Company, which position he held at the time of his death.

On May 18, 1920, Carl W. Clarke was united in marriage to Miss Marzie Masters of Enid. To this union were born two daughters, Nancy Lee, now aged five, and Caroline May, aged four. This loving family is left to mourn the loss of husband and father.

During his student days, Carl became a member of the Sigma Nu and Sigma Gamma Epsilon fraternities. Later he was elected to membership in

other societies, among them the University Club, the Technical Club, and the American Association of Petroleum Geologists. He was also a member of the Masonic order.

Among his friends in the profession and among his business associates, Carl W. Clarke was recognized as a geologist of exceptional ability. His was not the academic mind which delighted in the study of abstract problems and the presentation of such studies in published papers. Rather he leaned toward the practical, economic application of scientific principles, and his thorough understanding of this phase of petroleum geology is attested by the remarkable advancement of the Darby Petroleum Company under his direction as well as by his own personal success. Though but thirty-one years of age Carl had already amassed a comfortable fortune through his investments.

While record of his able work as a geologist may not be found in written reports published over his name, his true worth as a comrade and a friend will remain forever in the hearts of those who were fortunate enough to know him well.

E. F. SHEA

TULSA, OKLAHOMA
November, 1928

LAURA LEE WEINZIERL

Mrs. Laura Lee Weinzierl, *nee* Laura Lee Lane, died very unexpectedly in Houston, Texas, on September 28, 1928, from a sudden and severe attack of asthma.

At the time of her death she was acting as a consulting micropaleontologist in association with Alexander Deussen, consulting geologist of Houston, Texas.

Mrs. Weinzierl was born in Louisville, Kentucky, July 28, 1900. Her early childhood days were spent in west Texas on a ranch. At the age of seven she accompanied her mother to Germany, where she lived for four years attending her first school while her mother was studying music. In the early part of 1911 she lived with her mother at Seven Oaks, Kent, England. In 1911 she returned to America with her mother and lived in San Antonio for a short time. She was taken by her grandmother and mother to Los Angeles, where she attended a public school for approximately two years. After some time her family returned to San Antonio, and she graduated from the San Antonio High School in 1917.

In the first year at the State University, her ambition was to major in English, but later, through the good advice and careful training of Professor Whitney, she chose geology as her profession, specializing the last years in paleontology. In the summer of 1922, through the recommendation of Professor Whitney and Miss Esther Richards (now Mrs. Paul Applin), then a paleontologist for the Rio Bravo Oil Company, she accepted a position as paleontologist with Alexander Deussen. Here she had her first practical experience, under the supervision of Miss Richards. She returned to the State University in the fall of 1922 and graduated in 1923.

In the summer of 1923 she returned to Houston, Texas, taking up her work as paleontologist with Mr. Deussen. When Mr. Deussen became associated



LAURA LEE WEINZIERL

with the Marland Oil Company, taking charge of the operations of this company in the Gulf Coast district of Texas, Mrs. Weinzierl went on the geological staff of the Marland. When the company withdrew from the Gulf Coast in January, 1928, she opened an office as consulting micropaleontologist, maintaining her office with that of Mr. Deussen.

On April 3, 1926, she was married to John F. Weinzierl, chief geologist for the North American Exploration Company.

She was a member of the American Association of Petroleum Geologists, joining this organization as an associate member in 1924, being later transferred to active membership. She has been an enthusiastic attendant of all meetings of the Association since the time of her admission to membership.

She was a charter member of the affiliated Society of Economic Paleontologists and Mineralogists, and a member of the Houston Geological Society.

She was co-author with Mr. Deussen of the paper on the Hockley Salt Dome, presented to the Houston meeting of the American Association of Petroleum Geologists in 1924, and published in the Salt Dome volume of the Association.

Mrs. Weinzierl's work in paleontology has been confined largely to a study of *Foraminifera*, and her active work was concerned with the use of these microfossils in identifying the geologic formations penetrated by wells drilled in the Gulf Coast. In these determinations and indentifications she had become very expert, and her determinations of geologic horizons and formations were recognized as beyond question by geologists concerned with Gulf Coast geology. However, her interest in paleontology was not confined to *Foraminifera*, as she was likewise greatly interested in all phases of paleontology and geology, although her professional work required that she devote most of her attention to *Foraminifera*.

She possessed a very charming personality and took a keen interest in everything with which she was concerned, and it is a matter of very great regret to her many friends that one whose future promised so much should be so suddenly removed by an untimely death from a life work just commencing.

ALEXANDER DEUSSEN

HOUSTON, TEXAS

October 18, 1928

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

FRANK A. HERALD, who was secretary of the Hoover for President Engineers National Committee, Oklahoma Division, has closed his campaign offices and is returning about 30 per cent of the contributions received. Mr. Herald is opening an office as geologist and petroleum engineer at 312 Exchange National Bank Building, Tulsa, Oklahoma.

W. F. BOWMAN and J. M. VETTER are now associated as consulting geologists, with offices in the Second National Bank Building, Houston, Texas. Mr. Vetter devotes part of his time to the Rio Bravo Oil Company, with which he was formerly associated as superintendent of the land department.

GEORGE SHEPPARD, chief geologist, Anglo-Ecuadorian Oilfields, Ltd., has been appointed state geologist to the Republic of Ecuador. Mr. Sheppard's address is Casillo 410, Guayaquil.

T. A. BENDRAT, consulting geologist, has returned to 120 Clay Street, Montgomery, Alabama, after a special course in *Foraminifera* at the University of Chicago.

FRANK CARNEY, who has been in charge of the geology and land departments of the National Refining Company since 1917, resigned that position, effective December 30, 1928, and, commencing February 1, will give a course in geography at Texas Christian University, Fort Worth, Texas.

By a decree of the Government of the U. S. S. R., the seismologic section of the V. A. Steklov Institute of Physics and Mathematics of the Academy of the Sciences of the U. S. S. R. has been reorganized as the Institute of Seismology. Prof. P. Nikiforoff, who has distinguished himself in several lines of pure and applied geophysics, has been made director of the institute. The Interdepartmental Seismic Commission and the network seismic observatories of the U. S. S. R. are attached to the institute.

MR. and MRS. GASTON H. PARRISH announce the birth of Robert Bell Parrish, on November 19, 1928, at Corpus Christi, Texas.

R. S. PATRICK, of Duluth, Minnesota, has just issued two valuable illustrated trade booklets, "How to Cut Carbon Costs," and "Diamond Core Drilling in Oil Field Practice."

W. HEINE, author of a textbook on applied geophysical methods, has been made chief of a newly organized consulting geophysical firm which will be associated with the firm Photogrammetrie Gm. b. H. and which will

specialize in the electrical methods of prospecting. The office of the company will be on the Sendlingertorplatz in Munich.

L. P. GARRETT, of Houston, Texas, who has for some time been in charge of the land and geological departments of the Gulf Production Company, has been promoted to third vice-president of the company.

J. ELMER THOMAS, petroleum analyst with Fenner & Beane at Fort Worth, Texas, has a paper on "The New Economics in Oil Production" in *Mining and Metallurgy* of December, 1928, and a paper on "Production Curtailment in Texas" in *The Oil Weekly* of December 7, 1928.

I. L. DUNN and JAMES O. LEWIS presented a paper on "Unit Operation, Delaware Extension Pool, Oklahoma" at the A. P. I. meeting in Chicago last month. The paper is printed in *The Oil Weekly* of December 7, 1928.

WALTER R. BERGER, formerly chief geologist in the Texas division of the Marland Production Company, is now in charge of the Marland Employees' Royalty Company's geological department in Texas and New Mexico, with headquarters at Fort Worth.

LON D. CARTWRIGHT, JR., formerly in charge of the subsurface laboratory of the California Company at Colorado, Texas, has resigned to accept a position on the geological staff of the Superior Oil Company of California, with offices at Carlsbad, New Mexico.

The Color Chart prepared under the auspices of the Division of Geology and Geography of the National Research Council for use in describing the colors of sedimentary and other rocks is now ready for distribution, and the filling of advance orders is under way. New orders will be filled, as long as the supply lasts, at the following prices:

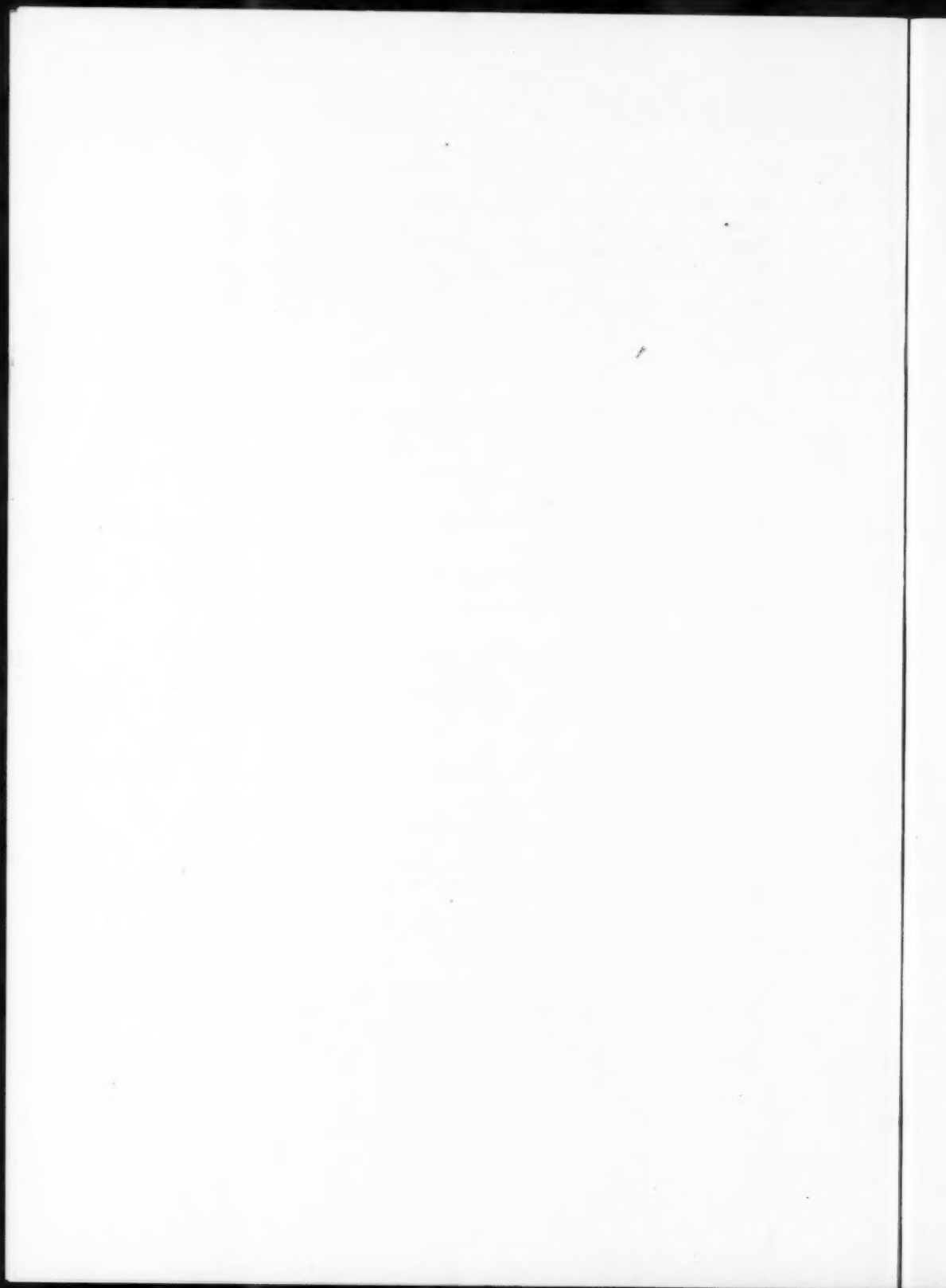
1 Chart \$ 0.75; 5 Charts \$ 3.50; 10 Charts \$ 6.50
25 Charts 15.00; 50 Charts 29.00; 100 Charts 55.00

The chart consists of two 5 by 8-inch sheets with 114 three-fourths-inch blocks of color printed on a gray background, by A. Hoen & Company of Baltimore. The colors have been selected from Ridgway's "Color Standards and Color Nomenclature" to cover the range of colors to be found in rocks, especially in sedimentary rocks, and have been arranged to conform as nearly as possible to Ridgway's system.

Orders should be sent to the chairman, Division of Geology and Geography, National Research Council, 21st & B Streets, NW., Washington, D. C. Checks should be made payable to the National Research Council.

The Society of Economic Paleontologists and Mineralogists has decided to hold its meetings Friday afternoon and Saturday morning (March 22 and 23) during the 14th annual convention of the A.A.P.G. At least two field trips are planned to follow the meetings,—one west from Fort Worth through the Lower Cretaceous and into the Pennsylvanian, and one through the Upper

Cretaceous into the Tertiary. It is hoped to provide the paleontologists with a tentative program before they start for the Fort Worth meeting. The committee will welcome papers on laboratory organization and methods as well as on pure paleontology and mineralogy. Highly technical papers such as species descriptions should be read by title. Those planning to present papers should communicate, not later than February 15, with the committee, GAYLE SCOTT, chairman, Texas Christian University, Fort Worth, Texas.



PROFESSIONAL DIRECTORY

SPACE FOR PROFESSIONAL CARDS IS RESERVED FOR ACTIVE
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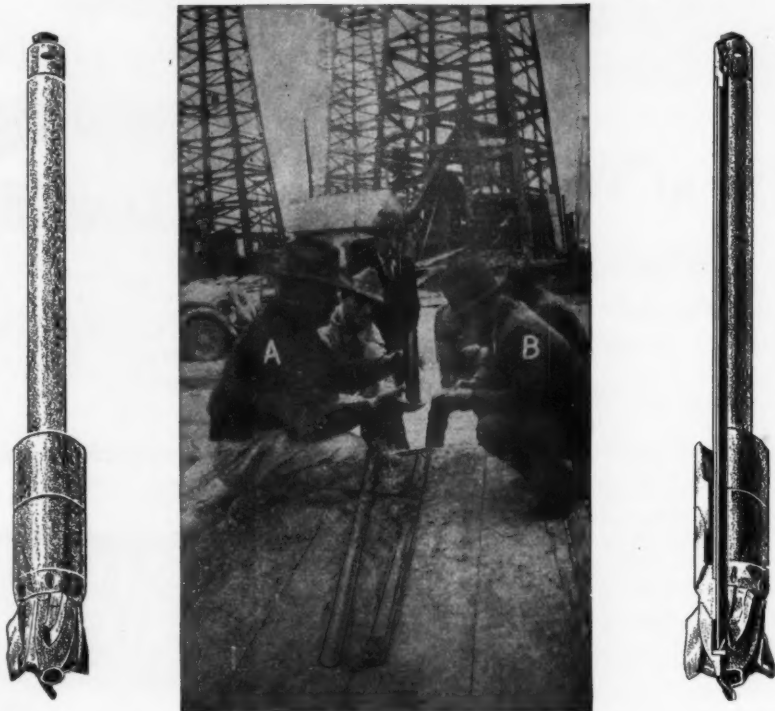
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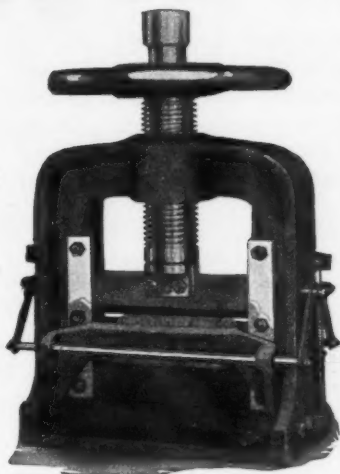
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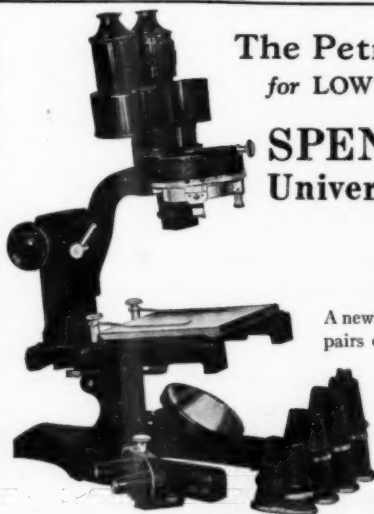
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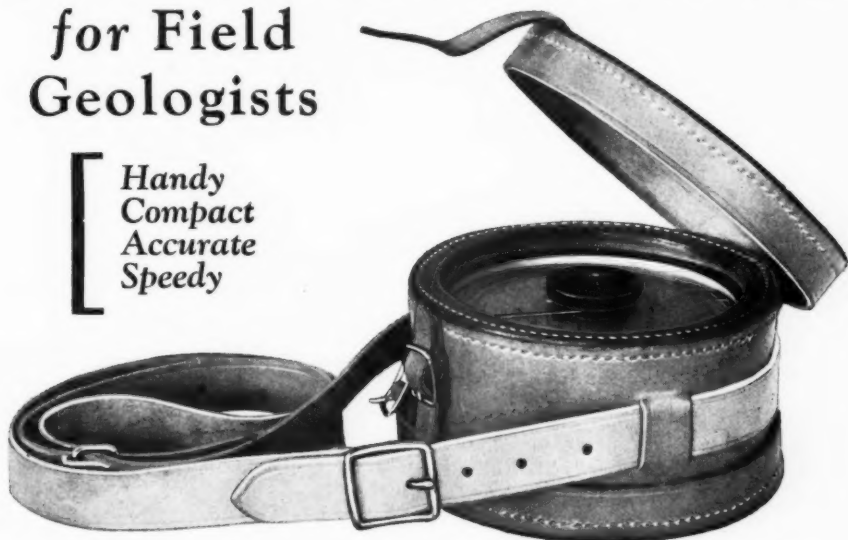
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